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(71) Applicant (for all designated States except US): **MI-CRONIC LASER SYSTEMS AB** [SE/SE]; IPR & Legal Department, Nytorpsvägen 9, S-183 03 Täby (SE).

(72) Inventor; and
(75) Inventor/Applicant (for US only): **SANDSTRÖM, Tor-björn** [SE/SE]; Banvägen 56, S-435 43 Pixbo (SE).

(74) Agent: **MICRONIC LASER SYSTEMS AB**; IPR & Legal Department, Nytorpsvägen 9, S-183 03 Täby (SE).

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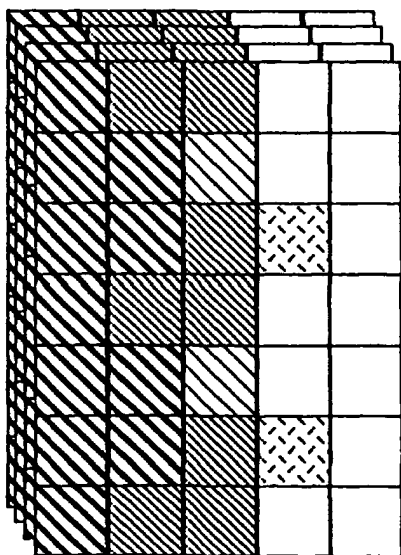
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(54) Title: METHOD AND APPARATUS FOR PATTERNING A WORKPIECE

(57) Abstract: The present invention relates to a method for creating a pattern on a workpiece sensitive to electromagnetic radiation. Electromagnetic radiation is emitted onto a computer controlled reticle having a multitude of modulating elements (pixels). The pixels are arranged in said computer controlled reticle according to a digital description. An image of said computer controlled reticle is created on said workpiece, wherein said pixels in said computer controlled reticle are arranged in alternate states along at least a part of one feature edge in order to create a smaller address grid. The invention also relates to an apparatus for creating a pattern on a workpiece. The invention also relates to a semiconducting wafer and a mask.

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## METHOD AND APPARATUS FOR PATTERNING A WORKPIECE

TECHNICAL FIELD

The present invention relates in general to techniques to obtain
improved images. In particular it relates methods of lithography
using a computer controlled imaging arrangement, such as for
instance a Spatial Light Modulator (SLM), with an improved
virtual grid. It also relates to an apparatus for patterning a
work piece comprising such a method.

DESCRIPTION OF THE BACKGROUND ART

Lithographic production is useful for integrated circuits,
masks, reticles, flat panel displays, micro-mechanical or
micro-optical devices and packaging devices, e.g. lead frames
and MCM's. Lithographic production may involve an optical
system to image a master pattern from a computer-controlled
reticle onto a workpiece. A suitable workpiece may comprise a
layer sensitive to electromagnetic radiation, for example
visible or non-visible light. An example of such a system is
described in WO 9945435 with the same inventor and applicant as
the present invention.

Said computer controlled reticle may for instance be a Spatial
Light Modulator (SLM) comprising a one or two dimensional array
or matrix of reflective movable micro mirrors; a one or two
dimensional array or matrix of transmissive LCD crystals; or
other similar programmable one or two dimensional arrays based
on gratings effects, interference effects or mechanical
elements, e.g. shutters.

Generally speaking pattern quality may be improved by multipass
writing. However, there are several different aspects of the
pattern quality that are improved by multipass writing, but not

necessarily at the same time. First, it is possible to create a
finer address grid in several passes than in one single pass.
Second, multiple passes with offset grid can remove the grid
effects due to the finite pixel size.

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Third, random errors (such as artifacts in the light path,
noise in the exposure dose, misplacement of beam or field used
for imaging) are statistically reduced by multiple passes,
e.g., four passes reduces the effects of random dose errors by
10    a factor of two (square root of four). Fourth, systematic
errors (such as dose fall of in corners of the image to be
written, distortion and focal plane curvature) can be reduced
by offset between the writing fields. Fifth, with multiple
writing passes it is possible to better correct for bad pixels.
15    Sixth, many multipass schemes give a softening of the edges,
and retention of edge acuity is a desirable property of a
multipass scheme.

Different rasterizing multipass schemes can be devised, but it
20    is a problem to find schemes that simultaneously give
improvements in all six aspects mentioned above.

Figure 3a illustrates a known method for creating a virtual
grid. In figure 3a it is shown an array of seven lines and 5
25    columns of pixels. Pixels in the two leftmost columns are set
to a maximum grayscale value. Pixels in the two rightmost
columns are set to minimum grayscale value. Pixels in a middle
column are set to an intermediate grayscale value. Figure 3a is
an example of analog modulation of feature edge pixels 301 in a
30    single pass in order to create a virtual grid. All pixels in
said middle column are set to the same value.

Figure 3b illustrates another known method for creating a
virtual grid. In this method four writing passes 305 are
35    written with binary doses (e.g. 100%, 50%, 25%, 12,5%). All

pixels in one single pass are set to equal grayscale values.
The virtual grid is created by turning on a column of feature
edge pixels in at least one writing pass, in figure 3b columns
of feature edge pixels are turned on in the top writing pass
5   and the second writing pass from bottom.
    Figure 3c illustrates yet another known method for creating a
virtual grid. In this method all four writing passes 305 are
written with the same dose. In at least one pass a column 304
of feature edge pixels are turned on, illustrated in figure 3c
10  to be the bottom writing pass and the second writing pass from
the bottom.

    Figure 4a illustrates another known method for creating a
virtual grid. In this method four 401 passes are written offset
15  with equal dose. The different writing passes are illustrated
in figure 4a to be offset relative to an origin 402. By turning
on edge pixels 403 in only some passes an edge of a feature to
be written can be fine positioned.

20  Figure 4b illustrates still another known method for creating a
virtual grid. This method utilizes a combination of the analog
modulation of feature edge pixels with offset passes which
gives a different analog value 404 in each pass.

25  Figure 5a illustrates a writing grid of four pixels in a single
pass writing strategy. A reference mark denoted with 501 is
arranged in middle of the grid.

    Figure 5b illustrates a known method for offsetting different
30  writing passes. Here four passes are used where two of them are
offset relative to the other two by a distance defined by a
half pixel size in two orthogonal directions parallel with the
pixel grid. By offsetting different writing passes in a
multiple writing strategy different imaging defects can more or
35  less effectively be hidden.

Figure 5c illustrates another known method for offsetting
different writing passes in order to hide the grid. In this
embodiment all writing passes are offset relative to each

5    other. One writing pass is offset in a first direction only,
another writing pass is offset in a second direction,
orthogonal to said first direction, and one writing pass is
offset in sad first and sad second direction simultaneously.
The offset in said first and said second direction is

10   illustrated to be half a pixel size.

It is in a general sense possible to make pattern fidelity
better by increasing the number of passes, but the cost is
high. Doubling the number of passes doubles the capital and

15   operating cost of the pattern generator per produced workpiece
and can in many cases be economically impossible.

In general, computer controlled reticles may be used for the
formation of images in a variety of ways. These reticles, such

20   as an SLM, include many modulating elements or pixels, in some
instances, a million or more pixels.

In WO 99/45440, with one common inventor to the present
application, is described a pattern generator with improved

25   address resolution. In said application the pixels can be set
in a number of states, larger than two, with one type of pixel
map inside pattern features, another type of pixel map outside
pattern features and intermediate pixel maps at a boundary of
pattern features. The intermediate pixel map is generated in

30   dependence of the placement of the boundary in a grid finer
than that of pixels of the SLM projected onto the workpiece.

Due to the fact that the line width and a space between two
lines in the pattern to be printed on the wafer are very small,

35   it puts a lot of demands on the printing method and the

apparatus using said method. Using an SLM, which provides for a
too coarse address grid may limit the resolution and accuracy
available for their use in optical imaging; e.g., the
production of printed patterns on a workpiece may be limited as
5    to its line widths and accuracy.

Therefore, there is a need in the art for a method, which
further fine-adjust the position of the element's edge in the
image created on the workpiece. There is also a need in the art
10   for an improved effectiveness of multipass averaging, i.e.,
reduced number of passes giving an improved fine-adjustment of
a feature edge.

SUMMARY OF THE INVENTION
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In view of the foregoing background, the fine adjustment of the
position of the element's edge in the image created on the
workpiece is critical for accomplishing line width in the range
of sub-micrometers both when using single pass or multiple pass
20   writing strategy.

The present invention applies to patterning a workpiece based on
a digital input data file, such as the writing of masks,
semiconductor wafers, optoelectronic devices, micro optical
25   devices, magnetic devices, super conducting devices, display
devices, and electronic interconnect structures such as MCMs.
The invention is independent of the mechanism of writing and
applies to laser and other electromagnetic beams, electron and
other charged particle beams. Beam is to be understood broadly
30   so that printing methods that uses projected areas such as SLMs,
cell projection are also included. Non conventional writing
mechanism are also included, such as atom beams, multi photon
processes, entangled photons, near field effects, direct current
exposure from scanning probes and thermal exposure.

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Accordingly, it is an object of the present invention to provide
an improved method for fine adjustment of the element's edge.

In a first embodiment, the invention provides a method for
creating a pattern on a workpiece sensitive to electromagnetic
radiation. Electromagnetic radiation is emitted onto a
computer-controlled reticle having a multitude of modulating
elements (pixels). The pixels are arranging in said computer
controlled reticle according to a digital description. An image
is created of said computer controlled reticle on said
workpiece, wherein said pixels in said computer controlled
reticle are arranged in alternate states along at least a part
of one feature edge in order to create a smaller address grid.

In another embodiment of the invention said pixels in said
computer controlled reticle along at least one feature edge
belong to a one-dimensional line of pixels.

In still another embodiment of the invention said image is
created in one writing pass.

In yet another embodiment of the invention said image is
created by means of a plurality of writing passes.

In a further embodiment of the invention said pixels in said
computer controlled reticle along at least one feature edge are
arranged differently in said plurality of writing passes.

In another embodiment of the invention, in a first writing
pass, at least a first pixel along at least one feature edge is
set to a first grayscale value and surrounded with pixels set
to at least one other gray scale value, and in at least one
other writing pass at least a second pixel along said at least
one feature edge is set to said first grayscale value with
surrounding pixels set to at least one other gray scale value

In still another embodiment of the invention four writing passes create the pattern.

In still another embodiment of the invention the pixels in the different writing passes set to said first grayscale value are non overlapping.

In still another embodiment of the invention said surrounding pixels are set to the same grayscale value.

In still another embodiment of the invention said surrounding pixels are set to the different grayscale values.

In still another embodiment of the invention said pixels in said computer controlled reticle along at least one feature edge belong to a line of pixels with a width of two pixels.

In still another embodiment of the invention said pixels in said computer controlled reticle along at least one feature edge belong to a lines of pixels with a width of three pixels.

In still another embodiment of the invention said pixels are micromirrors in an SLM.

In another embodiment of the invention said pixels are transmissive.

Another aspect of the present invention is to provide an improved apparatus for fine adjustment of the element's edge.

In a first embodiment, the invention provides an apparatus for creating a pattern on a workpiece sensitive to electromagnetic radiation. Said apparatus comprising a source to emit electromagnetic radiation onto a computer controlled reticle having a multitude of modulating elements (pixels), a

projection system to create an image of said computer

controlled reticle on said workpiece, wherein said pixels in

said computer controlled reticle are arranged in alternate

states along at least a part of a boundary of at least one

5     element to be patterned, in order to fine-adjust the position

of an edge of said element in said image to be created on the

workpiece.

In a first embodiment of the invention said pixels in said

10    computer controlled reticle along at least one feature edge

belong to a one-dimensional line of pixels.

In another embodiment of the invention said image is created in

one writing pass.

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In still another embodiment of the invention said image is

created by means of a plurality of writing passes.

In still another embodiment of the invention said pixels in

20    said computer controlled reticle along at least one feature

edge are arranged differently in said plurality of writing

passes.

In still another embodiment of the invention, in a first

25    writing pass, at least a first pixel along at least a part of

one feature edge is set to a first grayscale value and

surrounded with pixels set to at least a second gray scale

value, and in at least a second writing pass at least a second

pixel along said part of said feature edge is set to said first

30    grayscale value with surrounding pixels set to at least said

second gray scale value.

In yet another embodiment of the invention the pattern is

created by four writing passes.

In yet another embodiment of the invention said pixels set to say first grayscale value in the different writing passes are non-overlapping.

5    In still another embodiment of the invention said pixels set to said first grayscale value in the different writing passes are spaced apart with at least one pixel.

In still another embodiment of the invention said surrounding
10   pixels are set to the same grayscale value.

In still another embodiment of the invention said surrounding pixels are set to the different grayscale values.

15   In still another embodiment of the invention said pixels in said computer controlled reticle along at least a part of one feature edge belong to a line with a width of two pixels.

In another embodiment of the invention said pixels in said
20   computer controlled reticle along at least one feature edge belong to a line with a width of three pixels.

In another embodiment of the invention said pixels are micromirrors in an SLM.
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In another embodiment of the invention said computer controlled reticle is a transmissive SLM.

Another aspect of the present invention is to provide an
30   improved wafer, which is patterned with a finer address grid.

In a first embodiment the invention provides a semi-conducting wafer comprising at least one integrated circuit, wherein said at least one integrated circuit is patterned by means of
35   electromagnetic radiation emitted onto a computer controlled

reticle having a multitude of modulating elements (pixels) in
at least one writing pass, said pixels in said computer
controlled reticle is arranged according to a digital
description, an image of said computer controlled reticle is

5      created on said wafer, wherein said pixels in said computer
controlled reticle are arranged in alternate states along at
least a part of one feature edge in order to create a smaller
address grid.

10     Another aspect of the present invention is to provide an
improved mask, which is patterned with a finer address grid.

In a first embodiment the invention provides a mask comprising
a pattern to be printed on a workpiece, wherein a mask
15     substrate is patterned in at least one writing pass by means of
electromagnetic radiation emitted onto a computer controlled
reticle having a multitude of modulating elements (pixels),
said pixels in said computer controlled reticle is arranged
according to a digital description, an image of said computer
20     controlled reticle is created on said mask substrate, wherein
said pixels in said computer controlled reticle are arranged in
alternate states along at least a part of one feature edge in
order to create a smaller address grid.

25     Another aspect of the present invention is to provide an
improved method for fine adjustment of an element's edge to be
imaged.

In a first embodiment the invention provides a method for
30     imaging a pattern on a surface based on a description in a data
file, where multiple writing passes is provided, a grid of
pixels in at least two passes is offset, the values of edge
pixels in the different passes are controlled, and the values
of edge pixels between at least two passes are coordinated by a

predetermined rasterizing rule so that the edge quality is optimized.

In another embodiment of the invention, said edge quality is
5     defined to be edge roughness.

In another embodiment of the invention, said edge quality is defined to be edge acuity.

10    In another embodiment of the invention said edge quality is defined to be critical dimension control (CDC).

In another embodiment of the invention said at least two adjacent edge pixels in at least one pass have unequal values.
15
In another embodiment of the invention, said rasterizing is non-linear.

In another embodiment of the invention said dividing each pixel
20    in at least two areas where a first area has a first weight function performs non-linear rasterizing and a second area has a second weight function.

Another aspect of the present invention is to provide a method
25    for creating a virtual grid.

In a first embodiment the invention provides a method for writing a pattern on a substrate based on a description in a data file and to create a virtual grid, where a sequence of
30    feature edge pixels is generated in a first writing pass, said sequence of feature edge pixels is displaced in at least a second writing pass, said sequences are at least partly superposed on said substrate.

In another embodiment said invention further comprising the
action of offsetting a grid of pixels in at least two passes.

In another embodiment said invention further comprising the
action of repeating said sequence of feature edge pixels
periodic along at least one feature edge.

In another embodiment of the invention, said sequence of
feature edge pixels is non periodic.

Another aspect of the present invention is to provide a further
method for creating a virtual grid.

In a first embodiment the invention provides a method for
writing a pattern on a substrate based on a description in a
data file and to create a virtual grid, wherein a first
sequence of feature edge pixels is generated in a first writing
pass, a second sequence of feature edge pixels is generating in
at least a second writing pass, said sequences are at least
partly superposing on said substrate.

In another embodiment of the invention, said first and second
sequences are periodic.

In another embodiment of the invention, said first and second
sequences are non-periodic.

In another embodiment of the invention, said pixels are on/off
pixels.

In another embodiment of the invention, said pixels are multi-
valued pixels.

In another embodiment said invention further comprising the
action of offsetting a grid of pixels in at least two passes.

In another embodiment of the invention, said at least one of
said feature edge pixels is divided into at least two regions
having different weight functions for accomplishing non-linear
rasterizing.

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BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and
the advantages thereof, reference is now made to the following
10    description taken in conjunction with the accompanying drawings,
in which:

FIG. 1a illustrates a first way of rasterizing a feature using a
single writing pass.

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FIG. 1b illustrates a second way of rasterizing a feature using
a single writing pass.

                            c
FIG. 1c illustrates a third way of rasterizing a feature using
20    four writing passes.

FIG. 2a illustrates a rasterized feature.

FIG. 2b illustrates an exposure dose as a function of individual
25    pixels.

FIG. 2c illustrates a smoothening of an edge.

FIG. 3a illustrates a first embodiment according to prior art
30    for creating a virtual grid.

FIG. 3b illustrates a second embodiment according to prior art
for creating a virtual grid.

FIG. 3c illustrates a third embodiment according to prior art for creating a virtual grid.

FIG. 4a illustrates a fourth embodiment according to prior art for creating a virtual grid.

FIG. 4b illustrates a fifth embodiment according to prior art for creating a virtual grid.

FIG. 5a illustrates a first embodiment according to prior art for creating pass offsets.

FIG. 5b illustrates a second embodiment according to prior art for creating pass offsets.

FIG. 5c illustrates a third embodiment according to prior art for creating pass offsets.

FIG. 6a illustrates a first embodiment according to the present invention offsetting different writing passes.

FIG. 6b illustrates the result of printing a star using the offset according to figure 6a.

FIG. 6c illustrates a second embodiment according to the present invention for creating pass offsets.

FIG. 6d illustrates the result of printing a star using the offset according to figure 6c.

FIG. 7 illustrates reference points using four writing passes according to the present invention.

FIG. 8 illustrates a first embodiment of a four pass writing strategy according to the present invention.

FIG. 9 illustrates a second embodiment of a four pass writing strategy according to the present invention.

5    FIG. 10 illustrates a third embodiment of a four pass writing strategy according to the present invention.

FIG. 11a illustrates a fourth embodiment of a four pass writing strategy according to the present invention.

10   FIG. 11b illustrates a fifth embodiment of a four pass writing strategy according to the present invention.

FIG. 12a-e illustrates the result of single pass feature edge pixel sequences.

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FIG. 13 depicts a graph showing the relation between virtual grid and line edge roughness.

FIG. 14 illustrates four writing passes with a long feature edge

20   pixel period according to the invention.

FIG. 15 depicts a graph showing the simulated edge roughness for each pass and the combined roughness.

25   FIG. 16 depicts the same graph as in figure 13 but with the edge roughness after four passes with displaced edge pixel sequences.

FIG. 17 depicts an algorithm for computing the edge pixel values with on off pixels.

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FIG. 18 depicts the same as in figure 1 but with a 65-valued pixel.

FIG. 19 depicts a combination of two methods for improving the

35   virtual grid.

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FIG. 20a illustrates one embodiment of a multipass scheme.

FIG. 20b illustrates another embodiment of a multipass scheme.

FIG. 21a and b illustrates the difference between two passes when the input feature edge moves one address unit.

FIG. 22 illustrates one embodiment of a multipass scheme.

FIG. 23a and b illustrates graphs showing edge roughness.

FIG. 24a and b illustrates procedures to calculate optimal or near optimal sequences of feature edge pixels.

FIG. 25a illustrates a non-linear rasterizing function.

FIG. 25b illustrates the same as figure 20 but wit non-linear rasterizing function.

FIG. 26a-c illustrates the accomplishment of non-linear rastarizing.

FIG. 27a-c illustrates the weight function for non-linear rasterizing using the displacement scheme in figure 7.

FIG. 28a-b illustrates another embodiment of the weight function.

FIG. 29 illustrates one embodiment of an inventive feature edge pattern in a Spatial Light Modulator (SLM).

FIG. 30 illustrates another embodiment of an inventive feature edge pattern in a Spatial Light Modulator (SLM).

FIG. 31 illustrates yet another embodiment of an inventive
feature edge pattern in a Spatial Light Modulator (SLM).

FIG. 32 illustrates still another embodiment of an inventive

5      feature edge pattern in a Spatial Light Modulator (SLM).

FIG. 33a illustrates a first writing pass of another embodiment
of an inventive feature edge pattern in a Spatial Light
Modulator (SLM).

10

FIG. 33b illustrates a second writing pass.

FIG. 33c illustrates a third writing pass.

15     FIG. 33d illustrates a fourth writing pass.

FIG. 33e illustrates a table representing the passes illustrated
in figure 5a-5d.

20     FIG.34 illustrates a pattern generator.

DETAILED DESCRIPTION OF THE PREFFERED EMBODIMENTS

Figure 1a illustrates a rasterized feature 102. A grid 101

25     comprising pixels 103 is aligned to an origin 104 of a
coordinate system. From figure 1a one can see that the grid is
somewhat to coarse Therefore the feature 102 may not be imaged
as accurate as desired.

30     Figure 1b illustrates the same feature as shown in figure 1a,
but here the feature is rasterized to a finer grid. The accuracy
of the rasterizing is two times better, but there are four time
more pixels to write, which may make this method more time
consuming relative the one illustrated in figure 1a.

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Figure 1c illustrates the same feature as shown in figure 1a rasterized to the same grid size but using four passes 105 with no offset. Different lithographical characteristics such as resist properties and time delays may make this method of

5      imaging more accurate than the one illustrated in figure 1a given that the different passes are imaged with equal doses.

Figure 2a illustrates a rasterized vertical line. Figure 2b illustrates an ideal exposure 202 of the rasterized line in

10     figure 2a. Smoothing by a finite resolution of an exposure beam gives an exposure dose denoted by 203 in figure 2b. Figure 2b shows the smoothening by the exposure, but chemical diffusion, developer transport and finite resolution of the resist or recording medium also gives a similar effect. Figure 2c

15     illustrates a rasterized feature comprising a step. The imaged feature will end up with a pattern illustrated by the dashed line. The smoothening of step 205 is caused by the finite resolution of the exposure beam according to what was described in connection with figure 2b. Pixel 206 will therefore receive

20     contribution from adjacent pixels.

Figure 6a illustrates an inventive method for offsetting different writing passes. In this embodiment four writing passes are offset relative to each other by a quarter of a pixel size

25     in two orthogonal directions. The passes are here illustrated to be offset along a diagonal line of the pixel. Generally with N passes, where N is an integer greater than two, passes are distributed along a diagonal line of a pixel by (pixel size)/N, i.e., with three writing passes a first pass is written in a

30     origin of coordinates, a second pass is written 1/3 of a diagonal line of a pixel away from said origin of coordinates and a third pass is written 2/3 of a diagonal line of a pixel away from said origin of coordinates.

Figure 6b illustrates a star written by said offset method as illustrated in figure 6a. It can be seen from figure 6b that there exists an unwanted asymmetry in the diagonals. This is caused by the fact that smoothening only occurs in directions

5      parallel with pixel sides but in directions deviating from that one will see coarse grid effects.

Figure 6c illustrates another inventive method for offsetting different writing passes. In this embodiment four writing passes

10     are distributed by the same amount but not along a straight line as illustrated in figure 6a. Here a first pas is written in an origin of coordinates. A second pass ¼ of a pixel size in an x direction and ½ of a pixel size in a negative y direction, x and y directions are parallel with the sides of the rectangular

15     pixels. A third pass is written ½ the pixel size in the x direction and ¼ of the pixel size in the y direction. A fourth pass is written ¾ of the pixel size in the x direction and ¼ of the pixel size in the negative y direction. By this offsetting method you will obtain symmetry in both directions parallel to

20     the sides of the pixel and also in both diagonals of said pixels.

Figure 6d illustrates the same star written by the method according to figure 6c. Here the symmetry is improved compared

25     to the star in figure 6b. By offsetting the writing passes according to the scheme illustrated in figure 6c symmetry is accomplished in all eight directions.

Figure 7 illustrates reference points for several pixels in four

30     passes 701, 702, 703, 704. It is possible to modify the displacement between the passes slightly by a small fraction of a pixel size unit to get a more uniform distribution of the reference points at the expense of a non-uniform division along the horizontal and vertical axis. The details of the rasterizer

35     algorithm and the error structure of the pattern generator

determine which is more favorable. Mirror images of the pattern
in figure 7 and 90 degrees rotation of it will be equally good.
The offsetting method according to figure 7 is particularly good
for hiding a grid pattern. You may of course use another number
5     of passes, in such case the pattern will look differently. The
offset between the passes should be chosen so that one will get
as good symmetry in x and y directions and both diagonals as
possible.

10    Figure 8 illustrates four writing passes according to the
invention with analog or multi-valued pixels. A middle column,
represent a feature edge pixel column. As can be seen pixels in
said column are set to different states. The pattern of the
pixels in the feature edge column in the four passes could be
15    equal or unequal. A finer address grid is accomplished by
dithering between different grayscale values.

Figure 9 illustrates four passes according to the invention with
edge pixels in more than one column. The pixels are multi-
20    valued. Here again the plurality of edge columns in one writing
pass could be equal or unequal in at least one other writing
pass. Pixels in different edge columns may have different
weights, which may be set differently from one case to another
depending for instance which pattern is to be imaged.

25

Figure 10 illustrates a multipass scheme according to the
invention. Here, passes with different dose create a fine
address grid, with some passes, typically those with high dose,
doubled in order to improve averaging. The passes with the same
30    dose, in figure 10 denoted with the same crosshatch, can have
their exposure fields and/or their pixel grid displaced in order
to improve image uniformity. Writing passes with high doses are
repeated due to the fact that averaging will have most impact
from those passes. Passes with the lower doses may mainly be
35    used for fine adjusting the address grid. Passes with higher

dose are used for the most significant bits in the address and passes with lower dose are used for the least significant bits in the address.

5     Figure 11a and 11b illustrate multipass schemes according to the invention with edge pixels to create a finer grid and edge pixel sequence or distribution in different passes being different. In figure 11a the different passes are written with essentially the same exposure. In figure 11b two passes are written with for

10    example 25% exposure and the other two with 100% exposure. The period of sequence in each pass is four, giving a combined grid of 1/16 of the pixel size. An example of an edge pixel sequence is illustrated to the right of the superposed passes in figure 11b. The two leftmost patterns may be written by 100% exposure

15    and the two rightmost patterns may be written by 25% exposure.

Figure 12a-e illustrates different edge pixel sequences. Edge pixel sequences may be periodic or non-periodic. The figures show periodic sequences with different periods and a resulting

20    image edge. Figure 12a illustrates a pixels sequence with period 1, i.e., all pixels have the same value. Clearly this will create a smooth edge.

Figure 12b depicts a pixel sequence with period two, giving a

25    virtual address grid two times finer than in figure 12a. The edge is still smooth due to the smoothening function of the exposure tool and process. The pixels are analog with for example 16 states and every second pixel at the feature edge may for example be set at 5/16 and the rest to 6/16.

30

Figure 12c illustrates a pixel sequence with period three, giving three times finer grid but starting to show line edge roughness (LER). The actual edge roughness depends on the trade off between pixel size, and the figure shows a typical example.

35

Figure 12d and 12e illustrates a pixel sequence of 4 and 10 respectively. In those two figures one can clearly see that the edge roughness increases with increased pixel sequence period.

5    Figure 13 depicts a graph showing the relation between virtual grid and line edge roughness using the scheme in figure 12. Both virtual grid and edge roughness are in relative to the pixel size.

10   Figure 14 illustrates four passes with a long edge pixel period 1401. Each pass taken alone will create a strong line edge roughness 1402. By displacing the pattern a number of pixels between the passes and superposing the passes will reduce the line edge roughness 1403 strongly.

15   Figure 15 illustrates two graphs showing the simulated edge roughness for each pass and the combined roughness. The two graphs show two different sequences corresponding to different placement of the feature edge. The graphs show that some
20   placements are better and some are worse, but for every placement a large reduction of the roughness is possible. The left graph in figure 15 illustrates displacement of a regular pixel edge pattern and the right graph shows superposition of irregular pixel edge patterns.

25   Figure 16 illustrates the same graph as in figure 13, but here with the edge roughness after four passes with displaced edge pixel sequences. The graph is based on a simulation with typical input parameters and shows that sequence lengths of up to 16 are
30   possible with four passes. Larger sequence lengths may cause a roughness being bigger than the grid.

Figure 17 illustrates an algorithm for computing the edge pixel values with binary (on/off) pixels and a sequence period of 5.
35   The feature edge is located 0.409 units onto a pixel in a middle

column. The sequence in beforehand determined to be 0, 2, 4, 1, 3. The criteria for setting a pixel to an on state in the feature edge column is that $P+(s_i/L)>1$, where P is the position of the feature edge, $s_i$ is the individual number in the sequence
5   and L is a length of the sequence.

Figure 18 illustrates essentially the same as figure 17, but here 65-valued pixels are used. In this case $0.409=16/64+0.009=(16+0.576)/64$. As we are using a multi-valued
10  pixel we are interested to know when we are going to change state from 16/64 to 17/64. Therefore P=0.576.

Figure 19 illustrates a combination of two methods for obtaining a finer address grid. An example is the use of analog edge
15  pixels in more than one row, as illustrated in figure 9, figure 32 and figure 33. An effectiveness of pixels in different columns may be different and the columns may combine in a linear or non-linear fashion. The use of two such methods can be used in the invention with a calibrated lookup table. Input data
20  gives a look-up value for each of the methods, in the example for the analog values in the columns. The look-up table typically more output bits than address bits, so that a 6-bit address may generate two 8-bit values. The 8-bit values are generated during a calibration step when the edge placements for
25  different combination of values are measured and mapped to the input values. In the more simple case of a single method the same look-up table structure may be used, but only with one output for each input.

30  Figure 20a and b illustrates a multipass scheme with different edge sequences in the different passes and where the passes are displaced relative to each other. Figure 20a illustrates the different sequences of the feature edge pixels. Figure 20b illustrates how the passes are overlaid. Because of the
35  displacement between the passes the dashed line, which represent

the feature edge, will show up in different locations in the different passes. For each position of the final edge position there is at least one combination of feature edge patterns, which most likely all are different, which will result in an

5      essentially smooth edge. The pixels in figure 20a and b are on/off pixels.

Figure 21a and b illustrates t hat the edge pixels may be completely reshuffled in the passes when the input edge move

10     only one address unit. Figure 21a illustrates two passes at one edge placement. Figure 21b illustrates the same two passes when the input edge has moved one virtual grid unit to the left compared to figure 21a. One pixel value has been changed from on to off (six pixels in on state in figure 21a and 5 pixels in on

15     state in figure 21b in the feature edge column) and then the pixels have been reshuffled for best LER and edge acuity.

Figure 22 illustrates four passes with a long and unequal periodic sequences giving a virtual grid of 1/28 of the pixel

20     size. The sequence length is 7. For each virtual grid step one pixel is flipped from off to on. After 7 steps the same sequences can be reused but with an order between the passes changed or rotated. It is not necessary that the sequences are periodic, non-periodic sequences can be found with essentially

25     the same properties. It is also possible to use more or fewer passes and different displacements between the passes or no displacement at all.

Two graphs showing the edge roughness in each pass and four

30     combined passes are illustrated in figure 23a and 23b. Figure 23a shows the bitmap for one feature edge placement and figure 23b for another feature edge placement. In figure 23a there is no low frequency contribution.

Figure 24a and b illustrates two methods for calculating optimal or near optimal edge pixel sequences for different edge locations. The computed sequences are computed off-line and tabulated for use during rasterization. Figure 24a illustrates a

5    binary sequence representing the edge pixels in different passes. The pixels used are two-valued pixels. Four passes are used with an inventive displacement scheme as described hereinabove. The sequence of edge pixels is illustrated to be non-periodic. This illustration in figure 24a is only one among

10   many alternative ways for accomplishing the invention. Figure 24a shows that one column of pixels in each pass is controlled by a sequence, i.e., there are four columns that are controlled in a four pass scheme. It is of course possible to control a four-pass scheme with other number of columns.

15
Figure 24b illustrates an algorithm for generating a sequence with good properties for each edge position given by an input address grid. An error diffusion algorithm may be used to generate starting binary sequences. Error diffusion algorithms

20   can be found in textbooks relating to computer graphics. Error diffusion algorithms give an approximately uniform distribution of 0s and 1s. The sequence may be further improved by iterative permutations of short sequences. Permutations preserve the average edge position while on the other hand affecting edge

25   roughness, which is evaluated in an imaging model. A simple imaging model may first be used for a quick generation of candidate sequences. Candidate sequences may then be further analyzed/evaluated by a more comprehensive model, e.g., by a commercial lithography simulation program. Once a sequence

30   satisfying the acceptance level has been found, the sequence is accepted and the algorithm moves to the next edge location.

Figure 25a and b illustrates a non-linear rasterizing function. The pixel or average column vs. the overlap between a feature in

35   input data and a pixel area. Figure 25a illustrates a graph

showing a linear function, a piecewise straight-line non-linear
function and a smooth non-linear function. All three are
idealized, since in reality they get truncated to staircase
functions. Figure 25b illustrates the same as figure 20, but

5      here with a non-linear rasterizing function giving better edge
acuity, since only two of the passes have edge pixels. Each
position of the feature edge may be independently optimized. The
virtual grid in figure 25b is 1/16 of a pixel size. By looking
at the pixels at the feature edge and using four writing passes,

10     one can use 100% exposure in one pass for feature edge pixels
and 0% exposure in another writing pass for feature edge pixels.
For the remaining two passes one can use a steeper rasterizing
function.

15     Figure 26a-c illustrates how non-linear rasterizing can be
accomplished in a super-sampling rasterizer. Inside each pixel a
feature is rasterized on a finer grid, the super-sampling super-
grid. The pixel value is the number of super grid points that
are set by the rasterizer. With equal weight on every super-grid

20     point, the rasterizing is linear, if a larger weight function is
applied to the super-grid points near the center of the pixel a
non-linear rasterizing function will result. In figure 26b a
weight function with a center square with a higher weight is
shown. In figure 26c a continuous weight function is illustrated

25     with a higher weight in a center than near the edges. By this
super-sampling a steeper rasterizing function may be
accomplished.

Figure 27a illustrates a weight function for non-linear

30     rasterizing using the displacement scheme in figure 7. Figure
27a illustrates pixel areas within a pass 2701 that fill the
area with four times overlap after four passes. The rectangular
areas 2702, with higher weight function, are smaller and fill
the area without overlap after four passes. The rectangles have

35     to be rotated by 90 degrees in two of the passes 2703. Super-

sampling over either of these two area sizes gives a correct
pixel representation of an input pattern, i.e., it is not
possible to place a small feature anywhere so that its area is
not reflected accurately by the pixel values. There are other

5      area shapes that have the same property with a different
overlap factor, e.g., 2 or 8. Since each of the two area shapes
give correct rasterizing, every linear combination of them is
also correct.

10     Figure 27b illustrates a pixel with a super-sampled grid. One
weight function is applied over the central rectangle and
another over the remainder of the pixel.

Figure 27c illustrates the weight function in figure 27b in
15     three dimensions. The height of a central area and a plateau may
be chosen arbitrarily based on the degree of non-linearity
wanted.

Figure 28a and b illustrates a weight function analog to figure
20     27b and c for two passes offset half a pixel size in x and half
a pixel size in y. By changing the weight between within the
rectangle and outside said rectangle one can change the property
of the non-linearity, i.e., the steepness of the non-linear
function will vary.

25

Figure 29 shows an exemplary embodiment of an apparatus 1 for
patterning a work piece 60. Said apparatus 1 comprising a source
30     10 for emitting electromagnetic radiation, a first lens
arrangement 50, a computer controlled reticle 30, a beam
conditioner arrangement 20, a spatial filter 70 in a Fourier
plane, a second lens arrangement 40.

The source 10 may emit radiation in the range of wavelength from
infrared (IR), which is defined as 780 nm up to about 20 nm, to
extreme ultraviolet (EUV), which in this application is defined
as the range from 100 nm and down as far as the radiation is
5       possible to be treated as electromagnetic radiation, i.e.
reflected and focused by optical components. The source 10 emits
radiation either pulsed or continuously. The emitted radiation
from the continuous radiation source 10 can be formed into a
pulsed radiation by means of a shutter located in the radiation
10      path between said radiation source 10 and said computer
controlled reticle 30. As an example can the radiation source
10, i.e. the source of an exposure beam, may be a KrF excimer
laser with a pulsed output at 248 nm, a pulse length of
approximately 10 ns and a repetition rate of 1000 Hz. The
15      repetition rate may be below or above 1000 Hz.

The beam conditioner unit may be a simple lens or an assembly of
lenses or other optical components. The beam conditioner unit 20
distributes the radiation emitted from the radiation source 10
20      uniformly over at least a part of the surface of the computer
controlled reticle 30. In a case of a continuous radiation
source a beam of such a source may be scanned over the surface
of the computer controlled reticle.

25      Between the radiation source 10 and the computer controlled
reticle 30, which may for instance be a spatial light modulator
(SLM), said beam conditioner unit is arranged, which unit 20
expand and shapes the beam to illuminate the surface of the SLM
in a uniform manner. In a preferred embodiment with an excimer
30      laser as the source the beam shape is rectangular, the beam
divergence different in x-direction and Y-direction and the
radiation intensity is often non-uniform over the beam cross-
section. The beam may have the shape and size of the SLM 30 and
homogenized so that the rather unpredictable beam profile is
35      converted to a flat illumination with a uniformity of, for

example, 1-2%. This may be done in steps: a first beam shaping
step, a homogenizing step and a second beam-shaping step. The
beam is also angularly filtered and shaped, so that the
radiation impinging on each point on the SLM has a controlled

5    angular sub tense.

The optics of the invention is similar to that of a wafer
stepper. In steppers the beam is homogenized in a light pipe, a
rectangular or prism-shaped rod with reflecting internal walls

10   where many mirror images of the light source are formed, so that
the illumination is the superposition of many independent
sources. The homogenization may also be performed by splitting
and recombining the beam by refractive, reflective or
diffractive optical components.

15

The SLM 30 is fed with a digital description of the pattern to
be printed. The pattern may firstly be made in an ordinary
commercially available drawing program. Before the pattern file
is fed to the SLM, said pattern file is divided and transformed

20   to a recognized formed for the SLM.

Figure 30 shows a Spatial Light Modulator (SLM) 200 comprising a
2-dimensional array of pixels, in this embodiment 8 rows 3001
and eight columns 3002, i.e. 64 pixels in total. In reality the

25   SLM may comprise several millions of pixels but for reasons of
clarity an SLM with few pixels is chosen.

Micromirror pixels may for instance be 20 x 20 $\mu$m. A projection
lens with a reduction of 200x will make one pixel on the SLM

30   correspond to 0.1 $\mu$m in the image on the workpiece. Each pixel
may be controlled to 64 levels, thereby interpolating the pixel
of 100 nm into 64 increments of 1.56 nm each.

The two leftmost columns of pixels 3010, 3011 and the two
rightmost columns of pixels 3016, 3017 are set in a so called
black state, i.e. the pixels are in a state which will not
create any radiation onto the workpiece, indicated in figure 1

5       by 0. The two columns in the middle 3013, 3014 are set in a so-
called white state, i.e. the pixel are in a state which will
create maximum radiation onto the workpiece, indicated in figure
30 by 100. Pixels in columns 3010, 3011, 3016 and 3017 are
outside feature pixels. Pixels in columns 3013 and 3014 are

10      inside feature pixels. Pixels in columns 3012 and 3015 are
boundary feature pixels. The boundary feature pixels are, as
indicated in figure 1, set along the boundary of the feature in
alternate states, in this case indicated by 74 and 75. In this
embodiment every second boundary feature pixel is set to 74 and

15      the rest to 75. As can be seen from the same figure, the states
of the boundary feature pixels in column 212 do not match the
boundary feature pixels in column 3015, i.e. the boundary
feature pixels indicated by 75 do not belong to the same rows.
In an alternative embodiment, the boundary feature pixels do

20      match each other, i.e. the boundary feature pixels indicated by
a same gray level are located in the same row.

As an alternative to setting every second boundary feature pixel
to one gray level and the rest to another gray level, every

25      second pair of boundary feature pixels may be set to alternate
states. With each pixel controlled into 64 levels, a pixel size.
of 100 nm on the workpiece, and by setting the boundary feature
pixels in the SLM in alternate states, an address grid of 0.78
nm is achievable in one writing step. In figure 30, the boundary

30      feature pixels are represented by single columns 3012, 3015.

A smoother feature edge will be created with every boundary
feature pixel set to a first gray scale value and the rest of
the pixels set to an adjacent gray scale value, which may be

higher or lower compared to if longer sequences of alternate
states are chosen in a single writing pass.

In an alternative embodiment, as illustrated in figure 31, the
5       boundary feature pixels are represented by two columns. In
figure 31 the leftmost and rightmost column 3110 and 3117
respectively are set to the black state and pixels in these two
columns are representing outside feature pixels. Inside feature
pixels are represented in figure two in columns 3113 and 3114.
10      Boundary feature pixels are represented in columns 3111, 3112,
3115 and 3116.

In this embodiment, every second pixel in a leftmost boundary
feature pixel column 3111 and a rightmost boundary feature pixel
15      column 3116 are set to 1 and the rest to 0 grayscale level. Here
the pixels in the leftmost boundary feature pixel column 3111
set to 0 match the higher value of the pixels in the other
boundary feature pixel column 3112, here 75, creating together
one of the feature edges on the work piece. The same applies for
20      the two columns 3115 and 3116 creating together another feature
edge on the workpiece, i.e. the 0's in the rightmost column 3116
match the higher value, here 75, of the pixels in the other
boundary feature pixel column 3115 and the 1's in the rightmost
column 3116 match the lower value, here 73, of the pixels in the
25      other boundary feature pixel column 3115.

Alternatively the reverse may apply, i.e. having two boundary
feature pixel columns creating one feature edge on the
workpiece, the higher alternate state (grayscale value) in one
30      of these columns may match the higher alternate state (grayscale
value) in the other of these columns.

Instead of extending the boundary feature pixel columns into
outside feature pixel columns, said columns may be extended into
35      inside feature pixel columns as illustrated in figure 32. In

figure 32 columns 3210, 3211, 3216 and 3217 represent outside
feature pixel columns. Columns 3212, 3213, 3214, 3215 represent
boundary feature pixel columns. Here we have no inside feature
pixel columns because the line to be written is only represented
by 4 columns, and two columns represent one edge of the line. As
can be seen from figure 32, all higher alternate values match
each other, i.e. the 100's in columns 3213 and 3214 match the
75's in column 3212 and 3215. Alternatively higher values in the
outmost boundary feature pixel columns 3212 and 3215 may match
lower values in the inmost boundary feature pixel columns 3213
and 3214.

Figure 33 illustrates still another embodiment of an inventive
feature edge pattern in a Spatial Light Modulator (SLM). Here
three columns represent the boundary feature pixels. The
leftmost and rightmost column 3310 and 3317 respectively are set
to the black state and pixels in these two columns are
representing outside feature pixels. Boundary feature pixels are
represented in columns 3311, 3312, 3313, 3314, 3315 and 3316.
There are no inside feature pixels represented in figure 33.

In this embodiment, every second pixel in a leftmost boundary
feature pixel column 3311 and a rightmost boundary feature pixel
column 3316 are set to 1 and the rest to 0 grayscale level.
Here, the pixels in the leftmost boundary feature pixel column
3311 are set to 0 and they are matching the higher gray scale
value of the pixels in the boundary feature pixel columns 3312,
3313, 3314, 3315. The 0 gray scale value match in this
embodiment 75 gray scale value in columns 3312 and 3315, where
the rest of the pixels in columns 3312 and 3315 are set to 74.
The 0 gray scale value match in this embodiment 100 gray scale
value in columns 3313 and 3314, where the rest of the pixels in
columns 3313 and 3314 are set to gray scale value 99 in. Columns
3311, 3312, 3313, 3314, 3315, 3316, 3317 are creating together
the feature edges of a straight line.

Figure 34a illustrates a first of four writing passes for
creating a straight line with a fine address grid. The pixels in
columns 3410, 3411, 3416 and 3417 are set to gray scale value

5     zero. The pixels in columns 3413 and 3414 are set to gray scale
value 100. Columns 3410, 3411, 3416 and 3417 are, according to
the previous language used in the former embodiments, outside
feature pixel columns and columns 3413 and 3414 are, using the
same language, inside feature pixel columns. Columns 3412 and

10    3415 are boundary feature pixel columns. In the first writing
pass all pixels in said boundary feature pixel columns are set
to a first grayscale value except for at least one pixel which
is set to a second gray scale value. In this embodiment as
illustrated in figure 34a, seven out of eight pixels in the

15    respective columns are set the gray scale value 75. One pixel in
column 3412 is set to gray scale value 74 and one pixel in
column 3415 is set to gray scale value 74. Here the gray scale
value 74 in columns 3412 and 3415 match each other i.e. they are
exactly opposite to each other. However, in an alternative

20    embodiment, said second gray scale value may not be equal in
both boundary feature pixel columns and may not be positioned
exactly opposite to each other.


Figure 34b illustrates a second writing pass out of four for

25    creating a straight line. The only difference between figure 34b
and figure 34a is that the second gray scale value in the
boundary feature pixel columns 3412 and 3415 have moved from the
third position from top in figure 34a to a top position in
figure 34b.

30
Figure 34c illustrates a third writing pass out of four for
creating a straight line. The only difference between figure 34b
and figure 34c is that the second gray scale value in the
boundary feature pixel columns 3412 and 3415 have moved from the

top position in figure 34b to a fifth position from top in figure 34c.

5      Figure 34d illustrates a fourth writing pass out of four for creating a straight line. The only difference between figure 34d and figure 34c is that the second gray scale value in the boundary feature pixel columns 3412 and 3415 have moved from the fifth position from top in figure 34c to a bottom position in figure 34c.

10

When superposing said first, second, third and forth writing passes the effect of said second grayscale value will be essentially the same as the lower grayscale value in boundary feature pixel columns 3412 and 3415 in figure 1.

15

Figure 34e illustrates a writing pass scheme in an embodiment of four writing passes and a pixel sequence length of eight pixels. 1:st, 2:nd, 3:rd, 4:th Columns represent one boundary feature pixel column in the first, second, third and fourth writing pass

20     respectively. Pixels in said boundary feature pixel column in the first writing pass, as illustrated in figure 34e in the leftmost column, are first set individually to a sequence of grayscale values. At least one of the grayscale values in said sequence of eight pixels differs from the other. With the

25     writing pass scheme as illustrated in figure 34e said at least one pixel, which differs from the other, will move around in the boundary feature pixel column and create a finer address grid when the respective writing pass are superposed on each other.

30     Alternatively, any number of pixels in the sequence may be used instead of the illustrated 8, for example 6, 12, 14 and 16 pixels. The invention is not limited to a single writing pass or four writing passes as illustrated by the figures, but can be employed with any number of writing passes, for example 2, 3 and

35     5.

CLAIMS

1. A method for creating a pattern with improved virtual
   grid on a workpiece sensitive to electromagnetic
   radiation comprising the actions of:
   - emitting electromagnetic radiation onto a computer
     controlled reticle having a multitude of modulating
     elements (pixels),
   - arranging the pixels in said computer controlled
     reticle according to a digital description,
   - creating an image of said computer controlled reticle
     on said workpiece, wherein said pixels in said
     computer controlled reticle are arranged in alternate
     states along at least a part of one feature edge in
     order to create a smaller address grid.

2. The method according to claim 1, wherein said pixels in
   said computer controlled reticle along at least one
   feature edge belong to a one-dimensional line of pixels.

3. The method according to claim 1, wherein said image is
   created in one writing pass.

4. The method according to claim 1, wherein said image is
   created by means of a plurality of writing passes.

5. The method according to claim 4, wherein said pixels in
   said computer controlled reticle along at least one
   feature edge are arranged differently in said plurality
   of writing passes.

6. The method according to claim 5, wherein, in a first
   writing pass, at least a first pixel along at least one
   feature edge is set to a first grayscale value and
   surrounded with pixels set to at least one other gray
   scale value, and in at least one other writing pass at
   least a second pixel along said at least one feature edge
   is set to said first grayscale value with surrounding
   pixels set to at least one other gray scale value

7. The method according to claim 6, wherein the pattern is created by four writing passes.

8. The method according to claim 6, wherein said at least one pixel in the different writing passes set to said first grayscale value are non overlapping.

9. The method according to claim 6, wherein said surrounding pixels are set to the same grayscale value.

10. The method according to claim 6, wherein said surrounding pixels are set to the different grayscale values.

11. The method according to claim 1, wherein said pixels in said computer controlled reticle along at least one feature edge belong to at least two lines of pixels.

12. The method according to claim 11, wherein said pixels in said at least two lines are weighted differently when forming said virtual grid.

13. The method according to claim 1, wherein said pixels are micromirrors in an SLM.

14. The method according to claim 1, wherein said pixels are transmissive.

15. An apparatus for creating a pattern on a workpiece sensitive to electromagnetic radiation comprising:

- a source to emit electromagnetic radiation onto a computer controlled reticle having a multitude of modulating elements (pixels),

- a projection system to create an image of said computer controlled reticle on said workpiece, wherein said pixels in said computer controlled reticle are arranged in alternate states along at least a part of a boundary of at least one element to be patterned, in order to fine-adjust the position of an edge of said element in said image to be created on the workpiece.

16. The apparatus according to claim 15, wherein said pixels
    in said computer controlled reticle along at least one
    feature edge belong to a one-dimensional line of pixels.

17. The apparatus according to claim 15, wherein said image

5       is created in one writing pass.

18. The apparatus according to claim 15, wherein said image
    is created by means of a plurality of writing passes.

19. The apparatus according to claim 18, wherein said pixels
    in said computer controlled reticle along at least one

10      feature edge are arranged differently in said plurality
    of writing passes.

20. The apparatus according to claim 19, wherein, in a first
    writing pass, at least a first pixel along at least a
    part of one feature edge is set to a first grayscale

15      value and surrounded with pixels set to at least a second
    gray scale value, and in at least a second writing pass
    at least a second pixel along said part of said feature
    edge is set to said first grayscale value with
    surrounding pixels set to at least said second gray scale

20      value.

21. The apparatus according to claim 20, wherein the pattern
    is created by four writing passes.

22. The apparatus according to claim 20, wherein said pixels
    set to said first grayscale value in the different

25      writing passes are non overlapping.

23. The apparatus according to claim 22, wherein said pixels
    set to said first grayscale value in the different
    writing passes are spaced apart with at least one pixel.

24. The apparatus according to claim 20, wherein said

30      surrounding pixels are set to the same grayscale value.

25. The apparatus according to claim 20, wherein said
    surrounding pixels are set to the different grayscale
    values.

26. The apparatus according to claim 15, wherein said pixels

35      in said computer controlled reticle along at least a part

of one feature edge belong to a line with a width of two pixels.

27. The apparatus according to claim 15, wherein said pixels in said computer controlled reticle along at least one feature edge belong to a line with a width of three pixels.

28. The apparatus according to claim 15, wherein said pixels are micromirrors in an SLM.

29. The apparatus according to claim 15, wherein said computer controlled reticle is a transmissive SLM.

30. A semi-conducting wafer comprising at least one integrated circuit, wherein said at least one integrated circuit is patterned by means of electromagnetic radiation emitted onto a computer controlled reticle having a multitude of modulating elements (pixels) in at least one writing pass, said pixels in said computer controlled reticle is arranged according to a digital description, an image of said computer controlled reticle is created on said wafer, wherein said pixels in said computer controlled reticle are arranged in alternate states along at least a part of one feature edge in order to create a smaller address grid.

31. A mask comprising a pattern to be printed on a workpiece, wherein a mask substrate is patterned in at least one writing pass by means of electromagnetic radiation emitted onto a computer controlled reticle having a multitude of modulating elements (pixels), said pixels in said computer controlled reticle is arranged according to a digital description, an image of said computer controlled reticle is created on said mask substrate, wherein said pixels in said computer controlled reticle are arranged in alternate states along at least a part of one feature edge in order to create a smaller address grid.

32. A method for imaging a pattern on a surface based on a description in a data file comprising the actions of:

- providing multiple writing passes,

- offsetting a grid of pixels in at least two passes,

5     - controlling the values of edge pixels in the different passes

- coordinating the values of edge pixels between at least two passes by a predetermined rasterizing rule so that the edge quality is optimized.

10

33. The method according to claim 32, wherein said edge quality is defined to be edge roughness.

34. The method according to claim 32, wherein said edge quality is defined to be edge acuity.

15    35. The method according to claim 32, wherein said edge quality is defined to be critical dimension control (CDC).

36. The method according to claim 32, wherein at least two adjacent edge pixels in at least one pass have unequal

20      values.

37. The method according to claim 32, wherein said rasterizing is non-linear.

38. The method according to claim 37, wherein said non-linear rasterizing is performed by dividing each pixel in

25      at least two areas where a first area has a first weight function and a second area has a second weight function.

39. A method for writing a pattern on a substrate based on a description in a data file and to create a virtual grid, comprising the actions of:

30     - generating a sequence of feature edge pixels in a first writing pass,

- displacing said sequence of feature edge pixels in at least a second writing pass,

- superposing said sequences at least partly on said
  substrate.

40. The method according to claim 39, further comprising the
   action of

5      - offsetting a grid of pixels in at least two passes.


41. The method according to claim 39, further comprising the
   action of

   - repeating said sequence of feature edge pixels
10       periodic along at least one feature edge.


42. The method according to claim 39, wherein said sequence
   of feature edge pixels is non periodic.

43. A method for writing a pattern on a substrate based on a
15   description in a data file and to create a virtual grid,
   comprising the actions of:

   - generating a first sequence of feature edge pixels in
     a first writing pass,

   - generating a second sequence of feature edge pixels
20     in at least a second writing pass,

   - superposing said sequences at least partly on said
     substrate.

44. The method according to claim 43, wherein said first and
   second sequences are periodic.

25 45. The method according to claim 43, wherein said first and
   second sequences are non-periodic.

46. The method according to claim 43, wherein said pixels
   are on/off pixels.

47. The method according to claim 43, wherein said pixels
30   are multi-valued pixels.

48. The method according to claim 43, further comprising the
   action of:

   - offsetting a grid of pixels in at least two pases.

49. The method according to claim 43, wherein at least one of said feature edge pixels is divided into at least two regions having different weight functions for accomplishing non-linear rasterizing.

50. The method according to claim 43, wherein said sequence of feature edge pixels belong to a one-dimensional line of pixels.

51. The method according to claim 43, wherein said sequence of feature edge pixels belong to at least two lines of pixels.

52. The method according to claim 51, wherein said pixels in said at least two lines are weighted differently when forming said virtual grid.

103

101

104

102
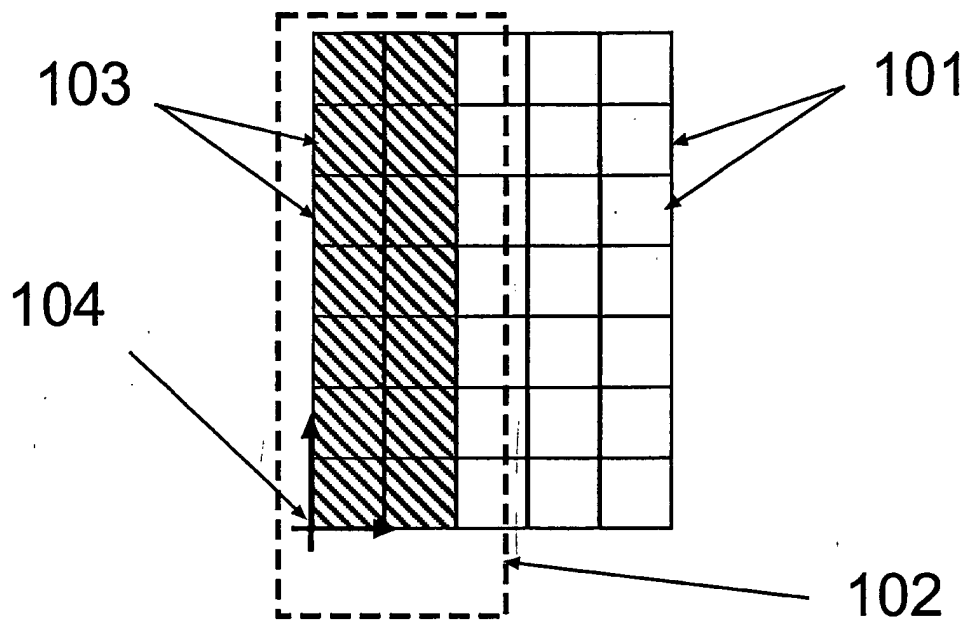
Fig. 1a

Fig. 1b

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Fig. 2a

Exposure dose



201

Fig. 2b



206

205
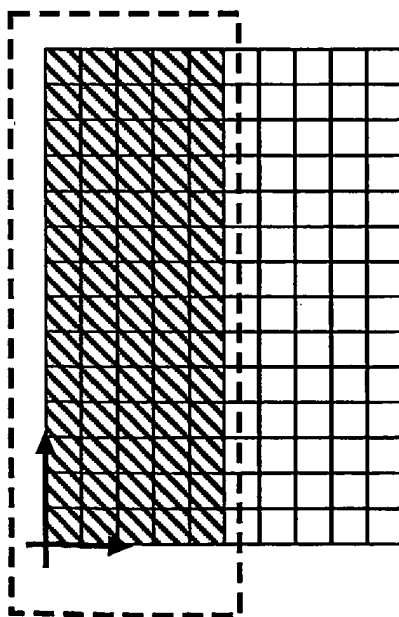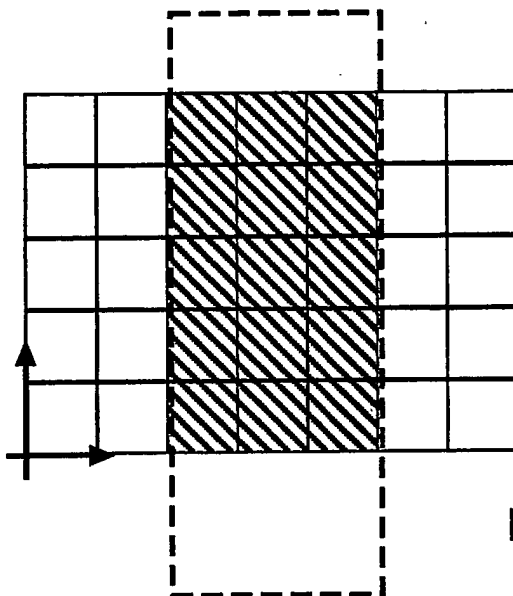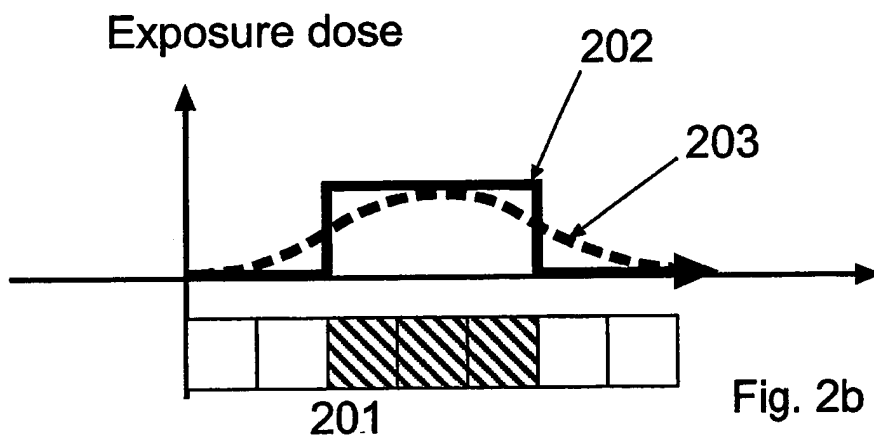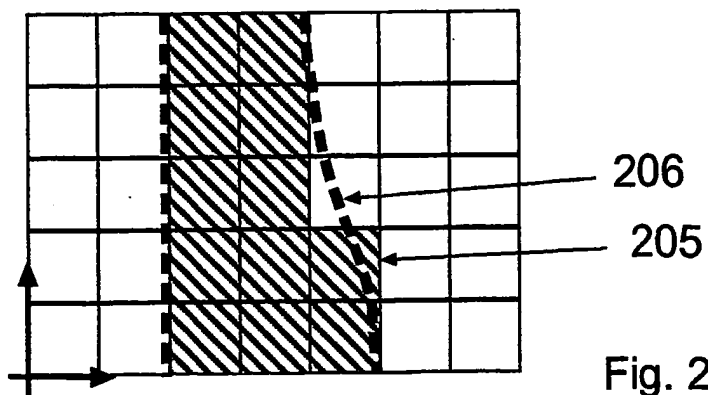
Fig. 2c

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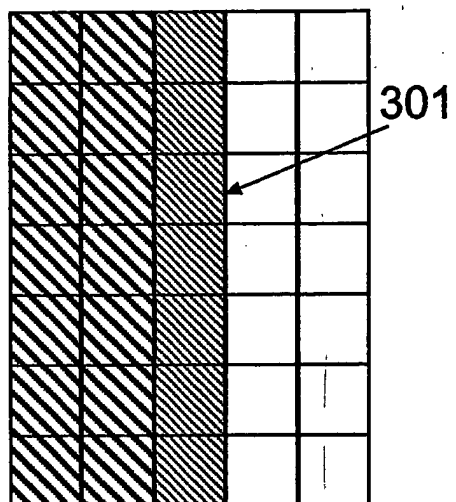


Fig3a Prior art
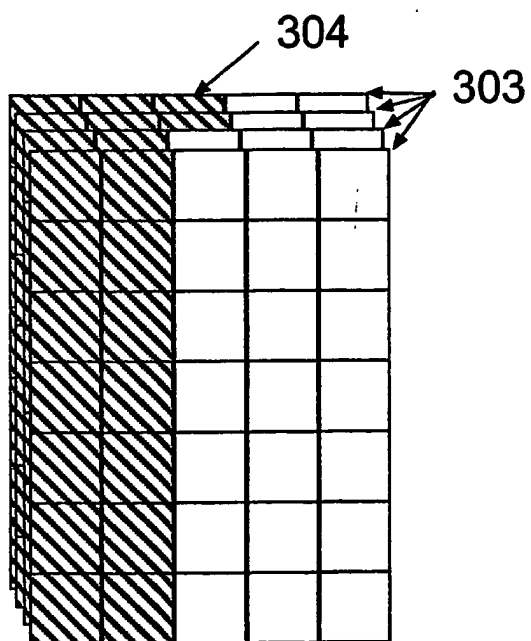


Fig3c Prior art



Fig3b Prior art
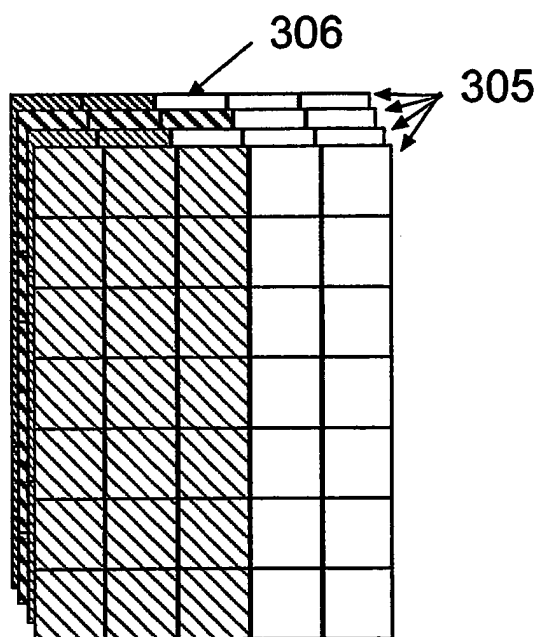
Fig. 4a Prior art
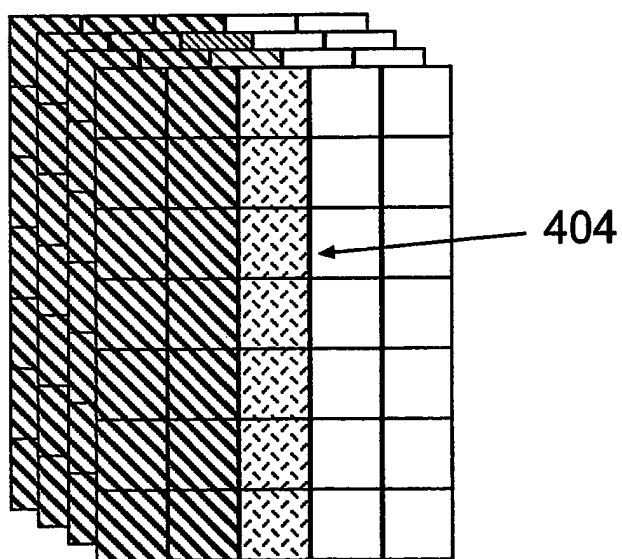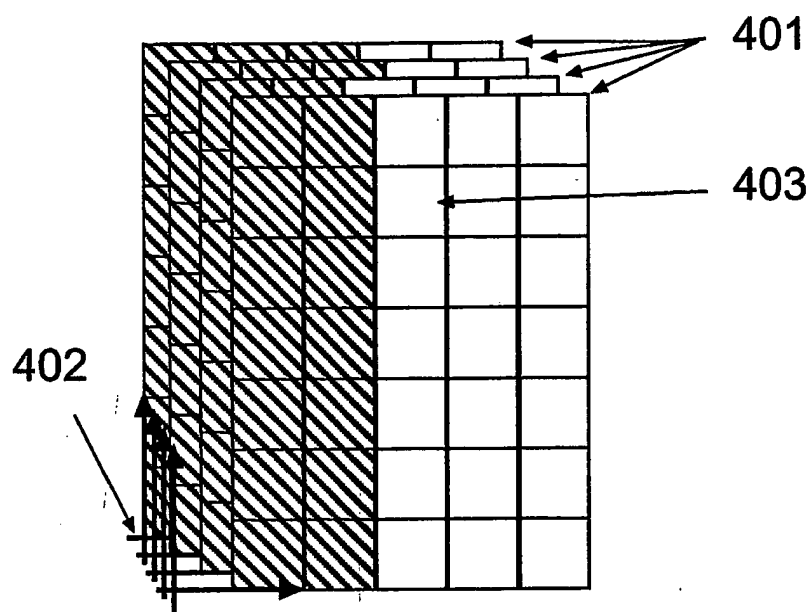


Fig. 4b Prior art

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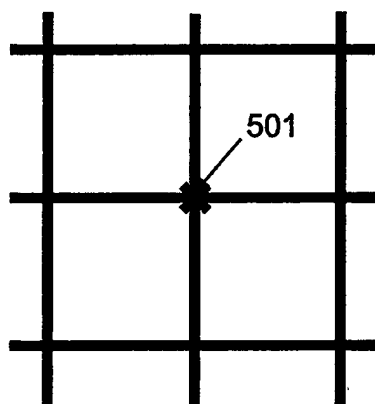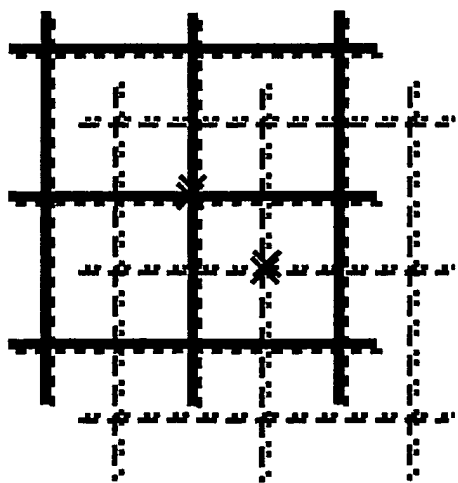


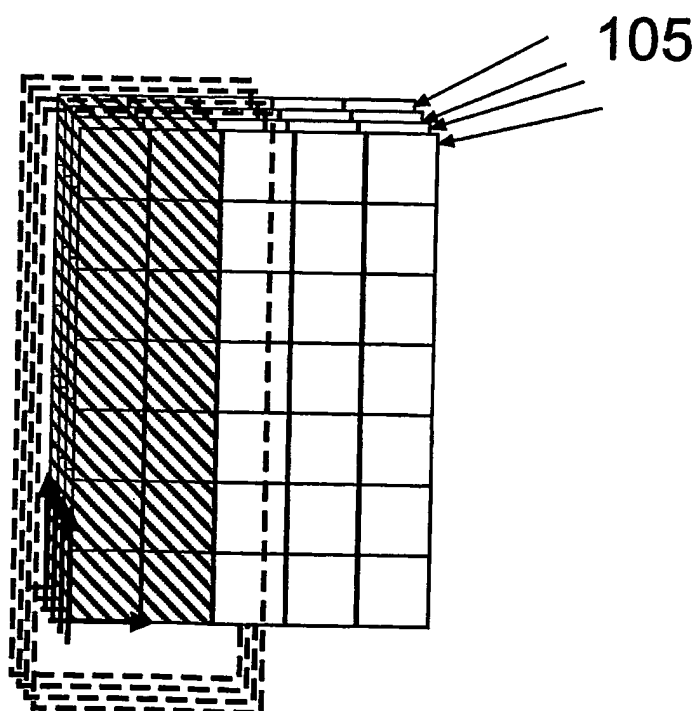Fig 5a: Prior art



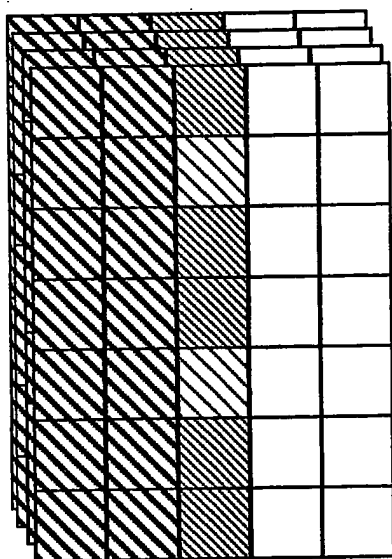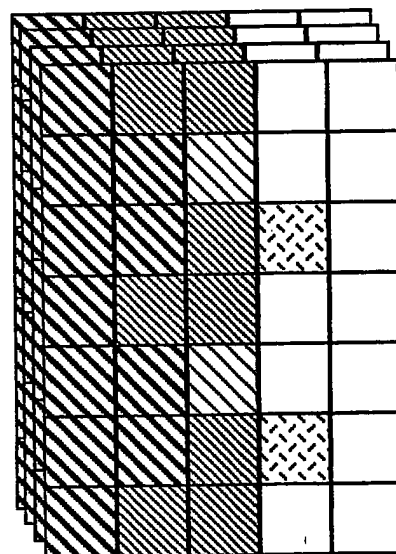Fig 5b: Prior art
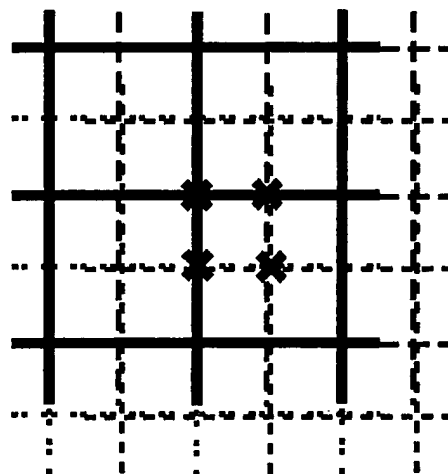


Fig 5c: Prior art
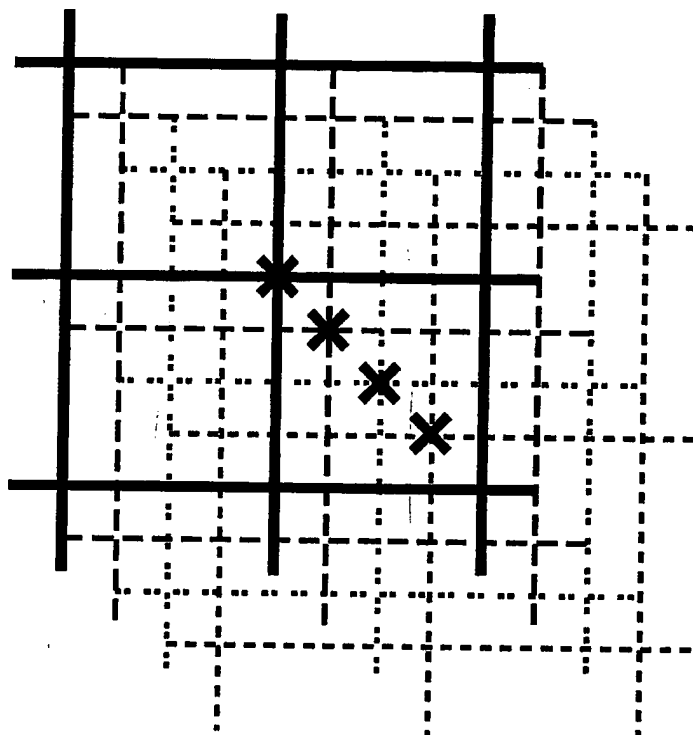
Fig. 6a
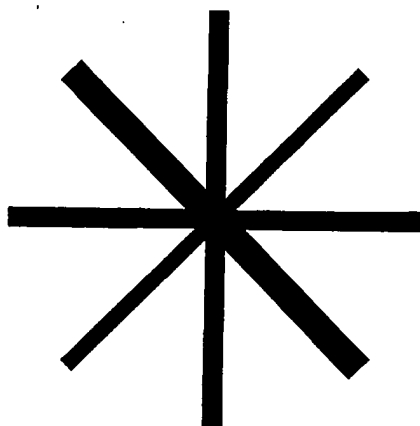


Fig. 6b
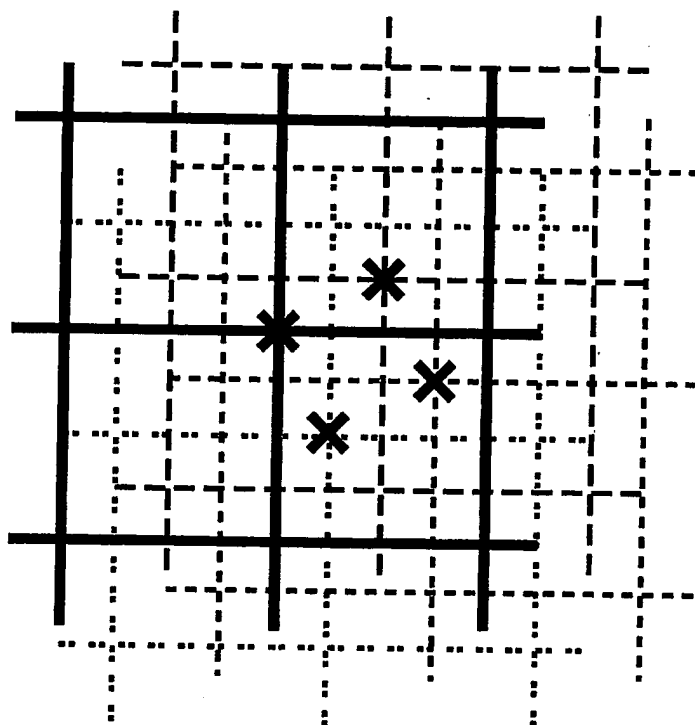
Fig. 6c
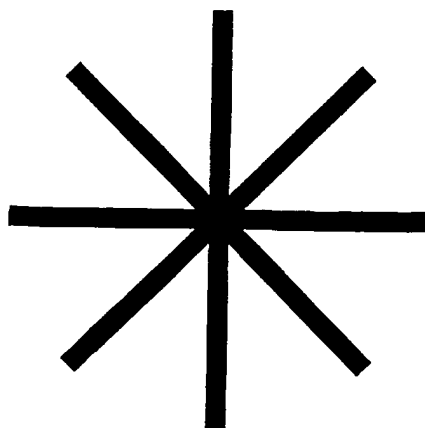


Fig. 6d
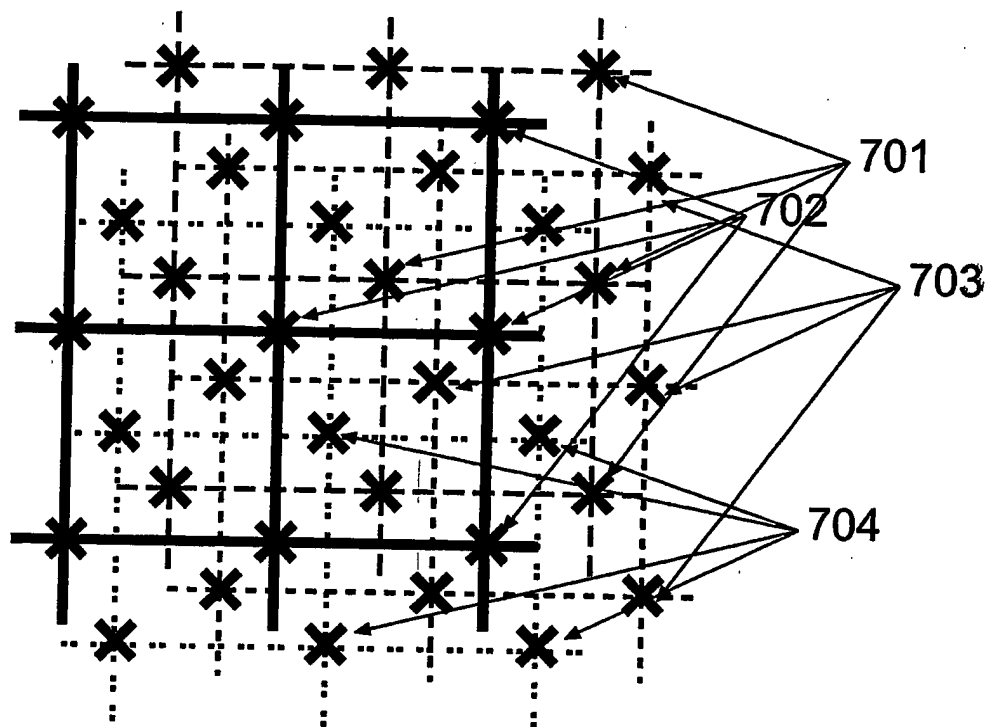
Fig. 7



Fig. 1c

Fig. 8



Fig. 9
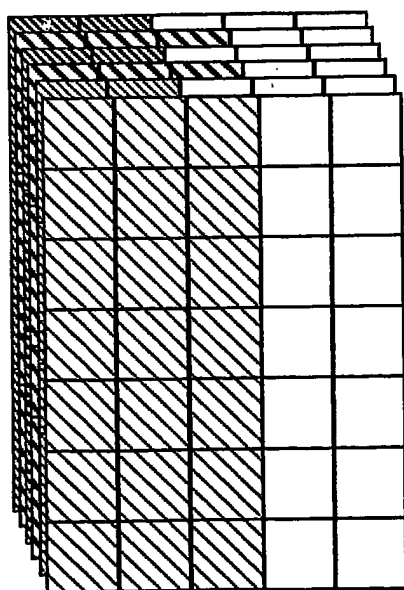


Fig. 10
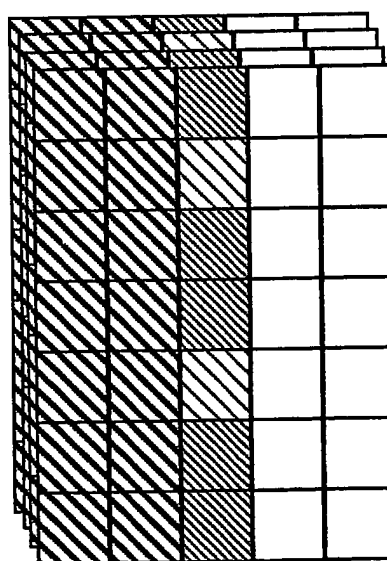


Fig. 11a

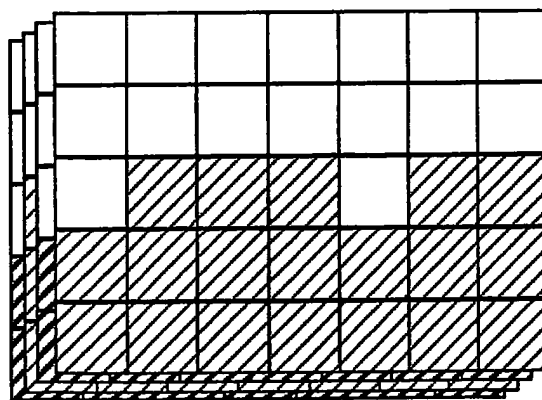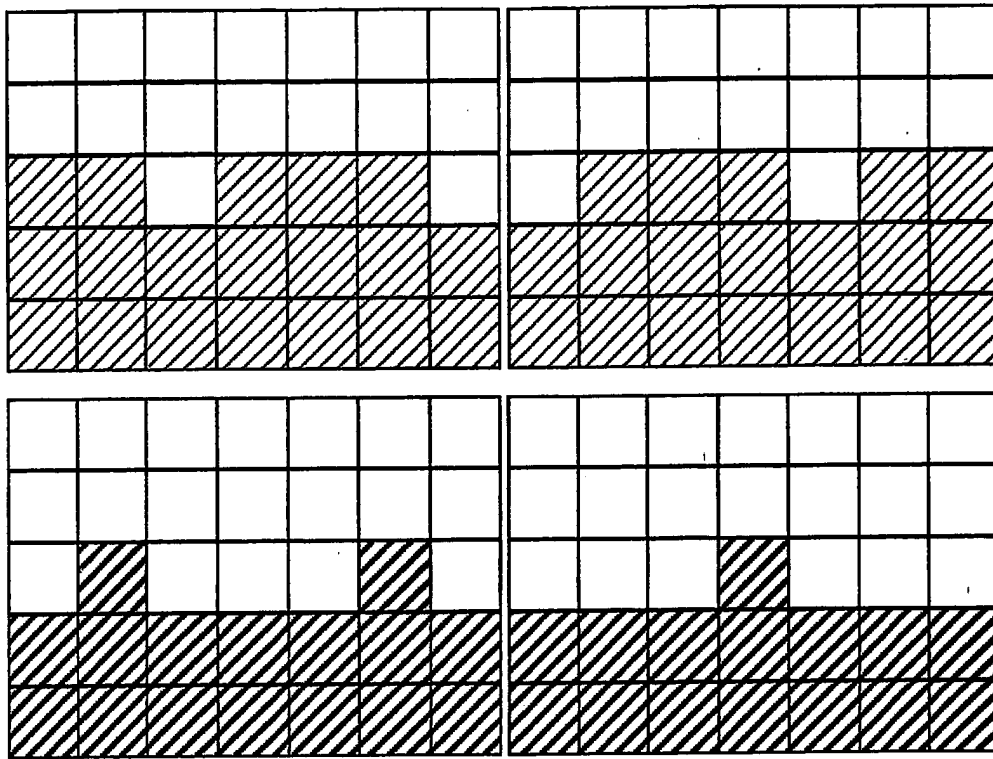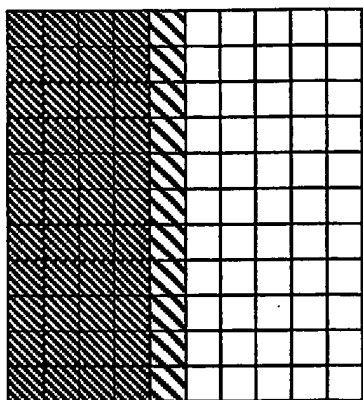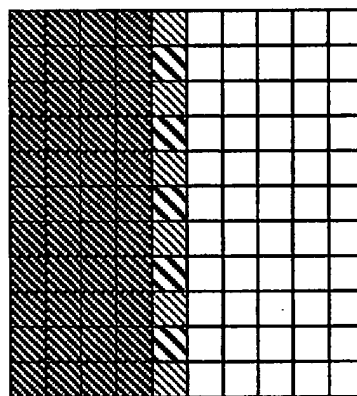Fig 11b

Fig. 12a

Fig. 12b

Fig. 12c
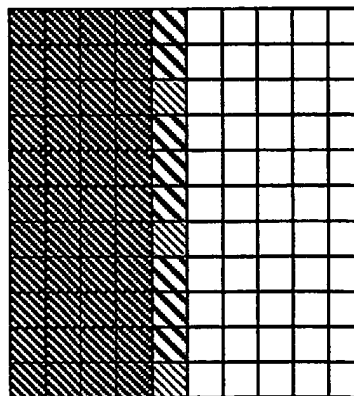
Fig. 12d
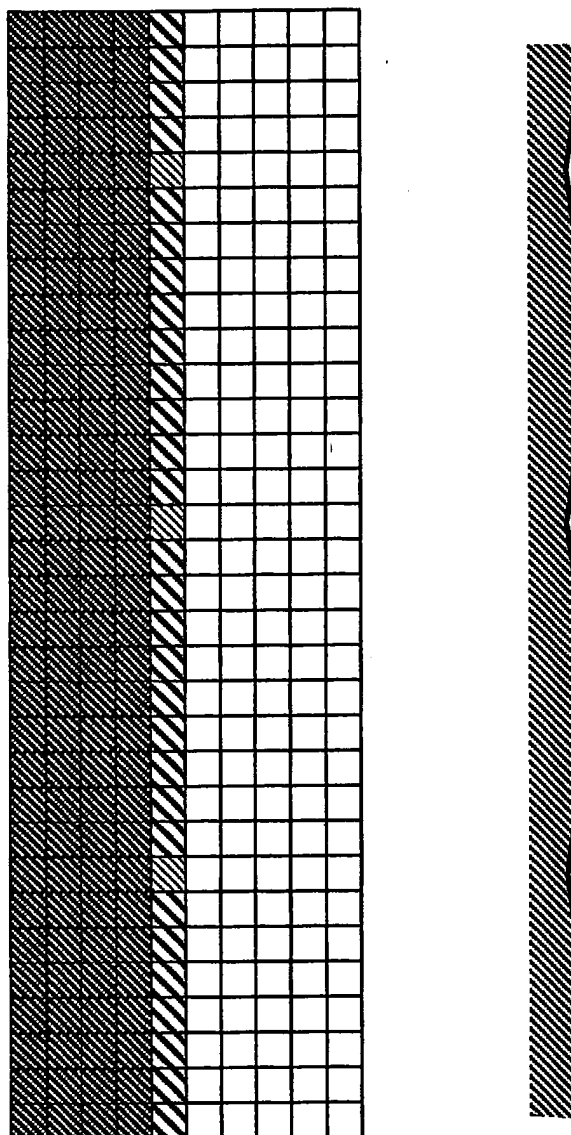
Fig. 12e

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Fig. 13

Fig. 14



Fig 15

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Fig. 16

$0/5 + 0.41 < 1$

$2/5 + 0.41 < 1$

$4/5 + 0.41 > 1$

$1/5 + 0.41 < 1$

$3/5 + 0.41 > 1$

$0/5 + 0.41 < 1$

$2/5 + 0.41 < 1$

$4/5 + 0.41 > 1$

$1/5 + 0.41 < 1$

$3/5 + 0.41 > 1$

period

0.409

0/5  2/5  4/5  1/5  3/5  0/5  2/5  4/5  1/5  3/5

Fig. 17

Fig. 18

| Address: | Data 1 | Data 2 |
|----------|--------|--------|
| 000001: | 00010010 | 0001 |
| 000010: | 00010011 | 0110 |
| 000011: | 00011001 | 0011 |
| 000100: | 00011100 | 1001 |
| 000101: | 00... | |
| 00... | | |

Input data

Method 1

Method 2

Physics

Calibration

Edge placement
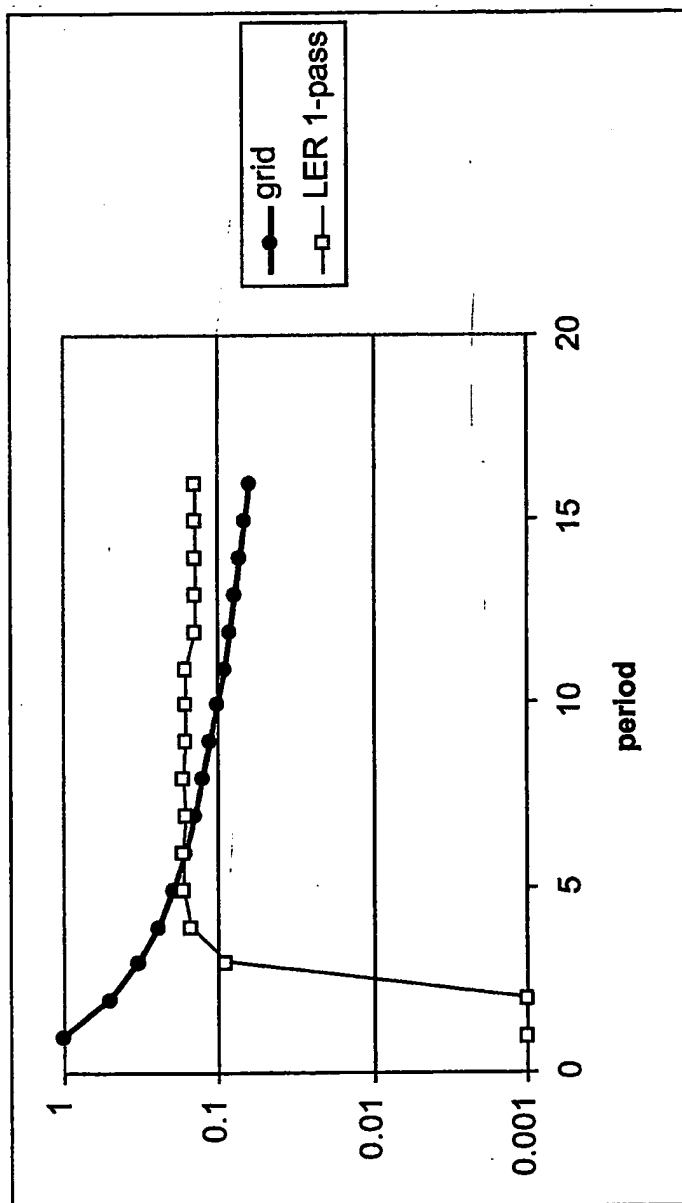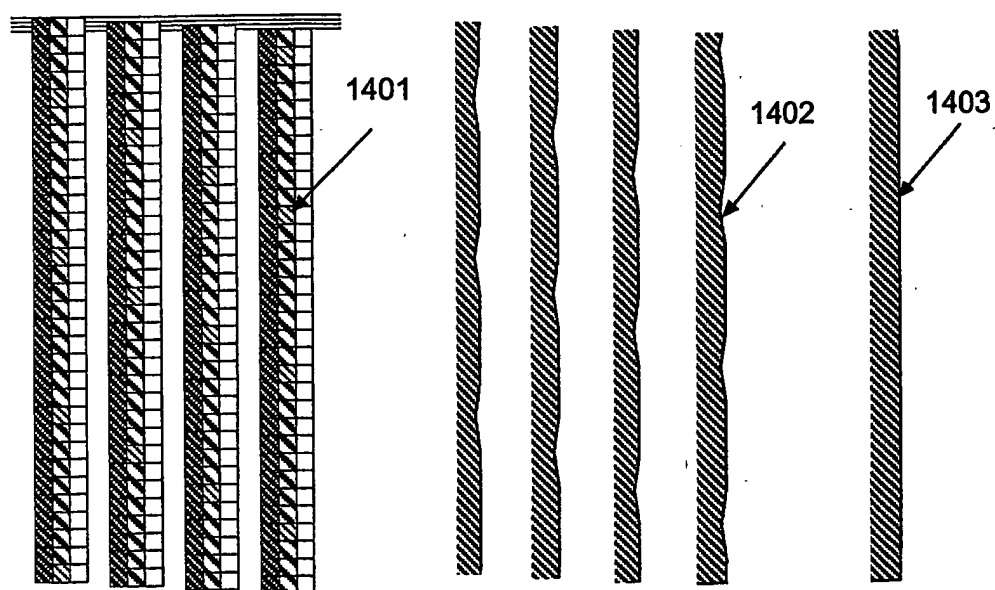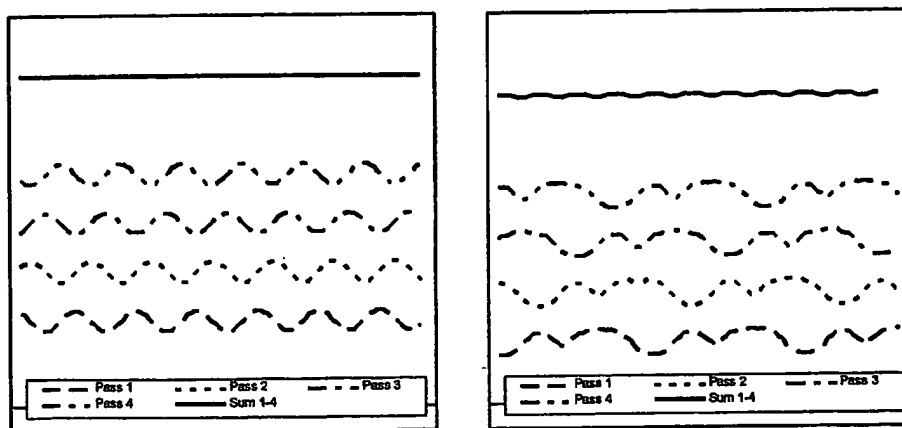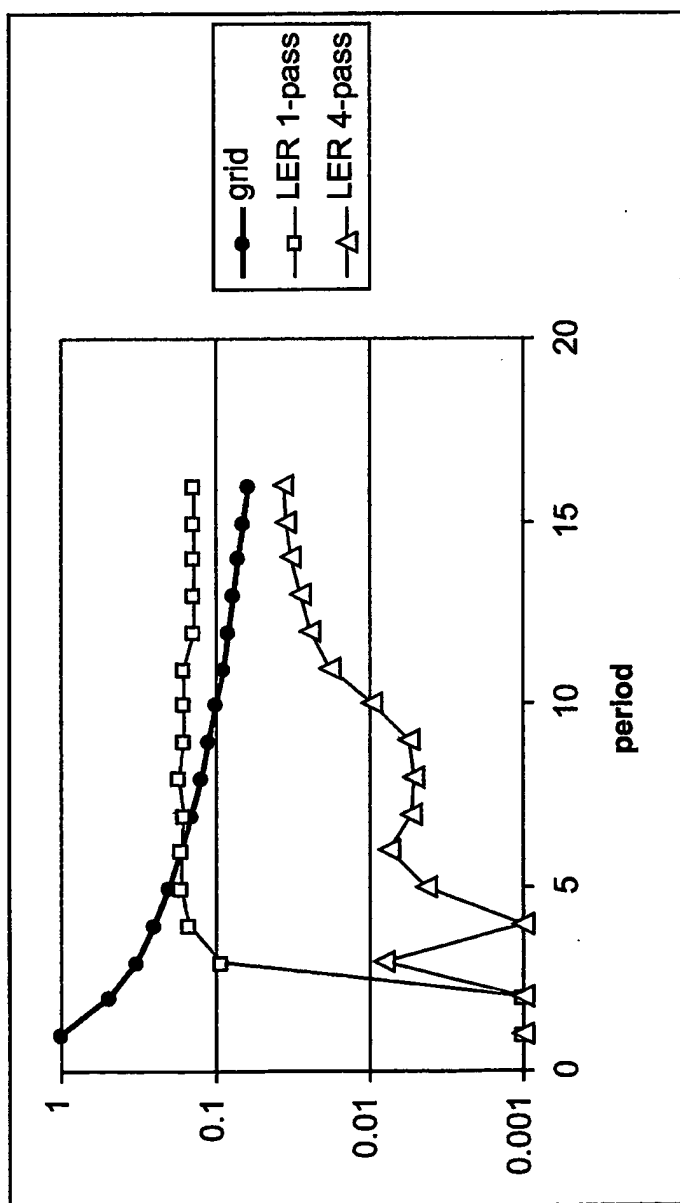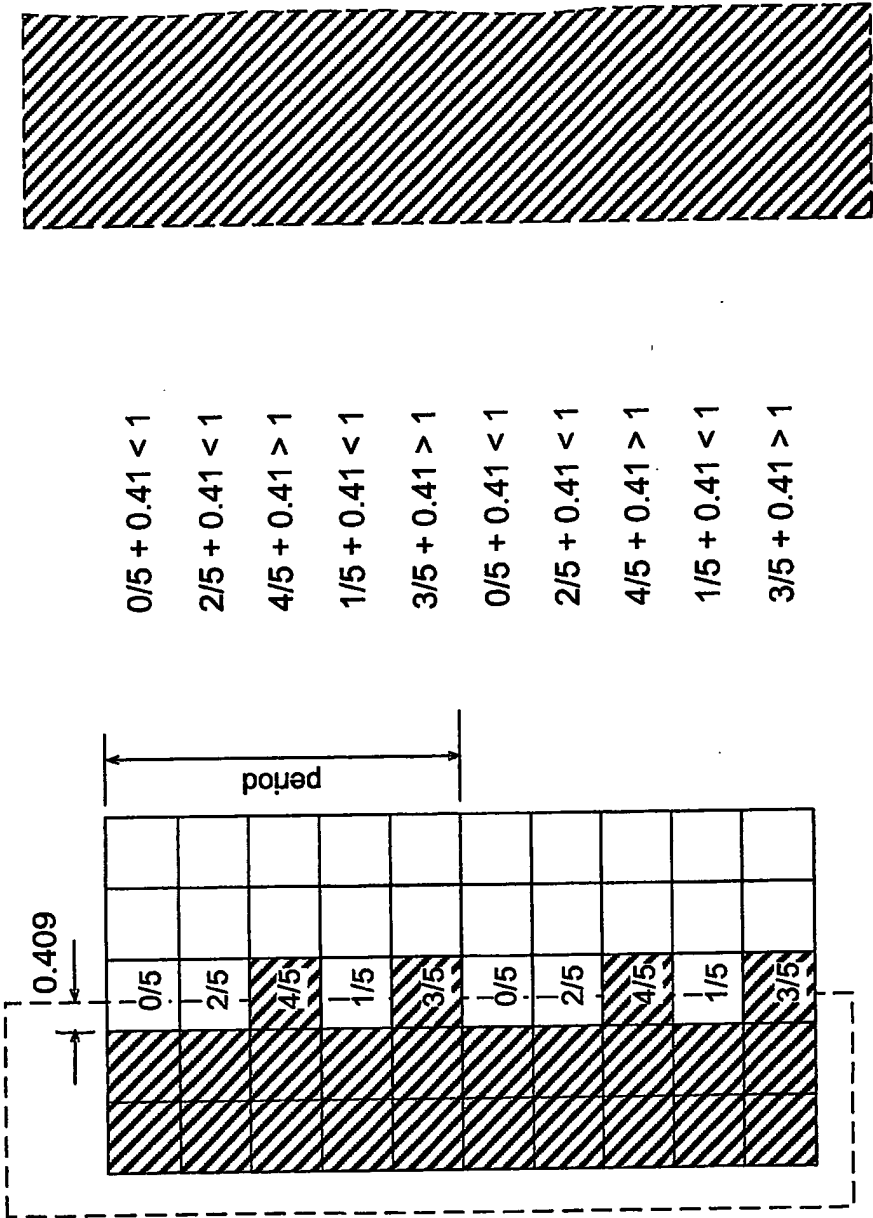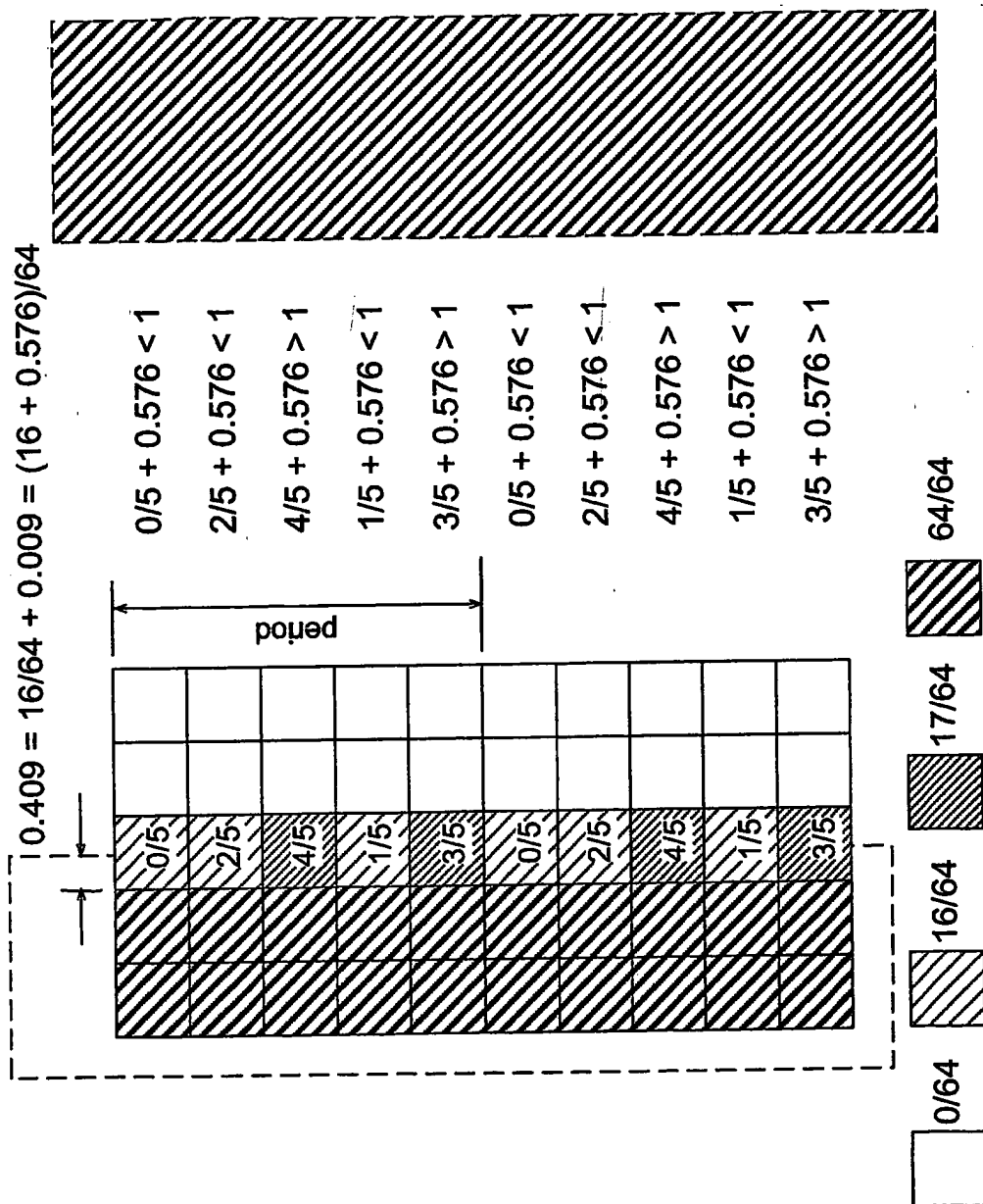
Fig. 19
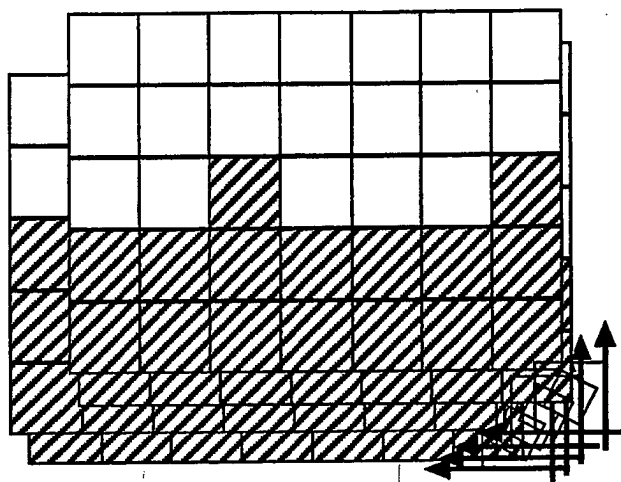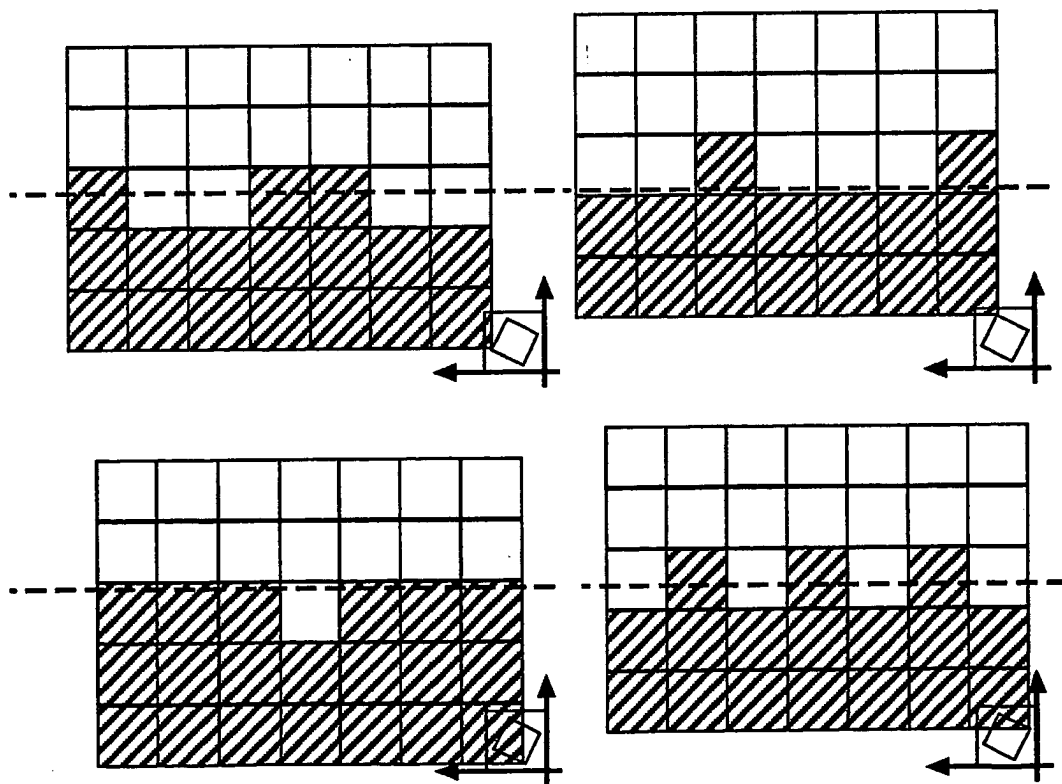
Fig. 20b



Fig. 20a

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Fig. 21a

Fig. 21b

Fig. 22

**Multipass edge placement**



Fig. 23a

Pixel grid in Pass 1

**Multipass edge placement**



Fig. 23b

Pixel grid in Pass 1

Fig. 24a

```
        ┌─────────┐
        │  Start  │
        └────┬────┘
             │
             ▼
     ┌───────────────┐
     │ Determine     │
     │ merit function│
     └───────┬───────┘
             │
             ▼
     ┌───────────────────┐
     │ Determine merit   │
     │ level of acceptance│
     └─────────┬─────────┘
               │
               ▼
     ┌───────────────┐
     │ Set first     │
     │ edge position │
     └───────┬───────┘
             │
             ▼
     ┌───────────────┐          ┌───────────────┐
     │ Calculate     │          │ Set next      │
     │ average       │          │ edge position │
     │ pixel value   │          └───────────────┘
     └───────┬───────┘
             │
             ▼
     ┌───────────────┐
     │ Use error     │
     │ diffusion to  │
     │ find a sequence│
     └───────┬───────┘
             │
             ▼
     ┌───────────────┐    ┌───────────────┐
     │ Evaluate merit│    │ Modify sequence│
     │ function      │    │ by piecewise  │
     └───────┬───────┘    │ permutations  │
             │            └───────────────┘
             ▼
        Acceptable?
             │
             ▼
      All edge positions?
             │
             ▼
        ┌─────────┐
        │ Finish  │
        └─────────┘
```
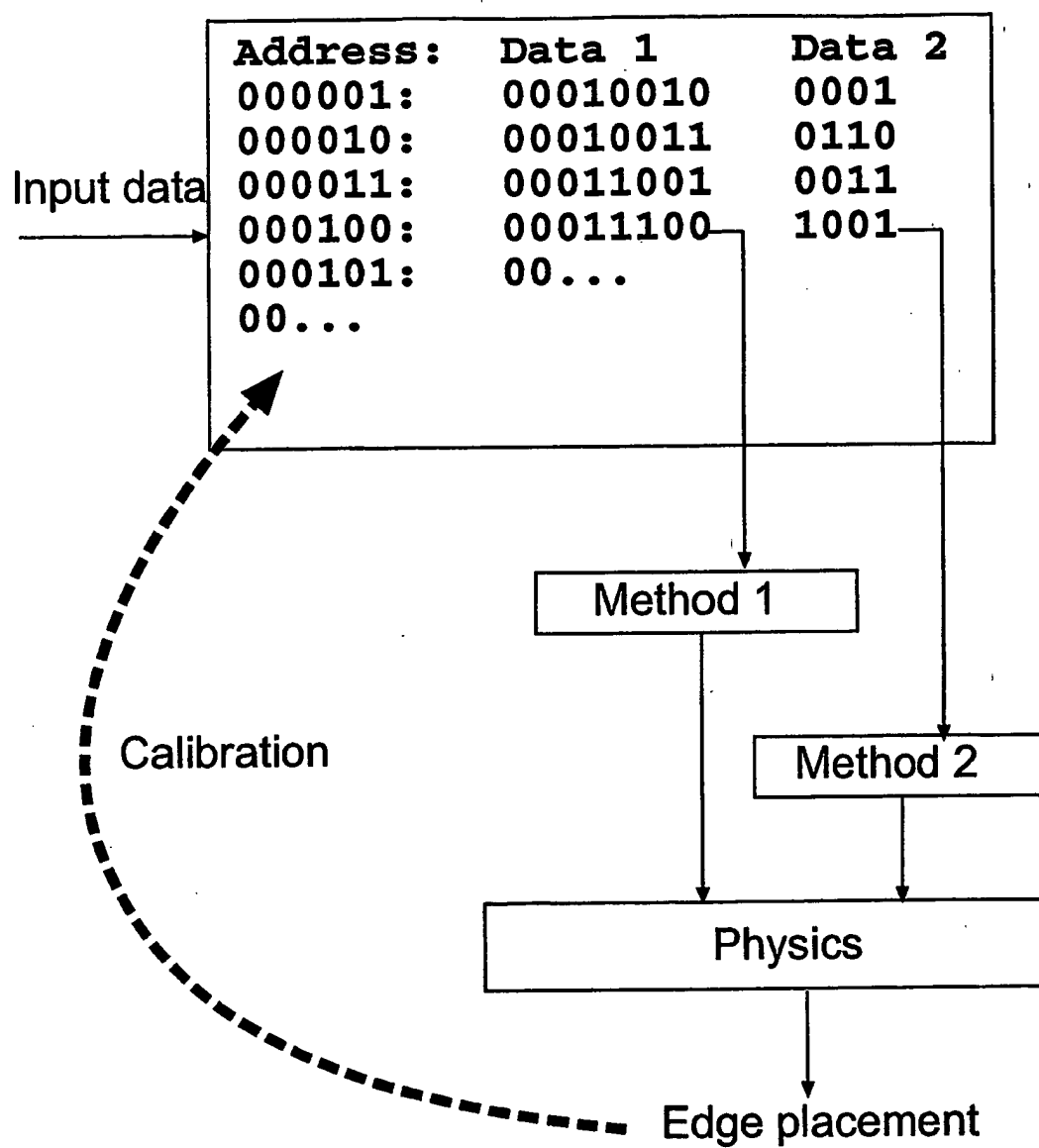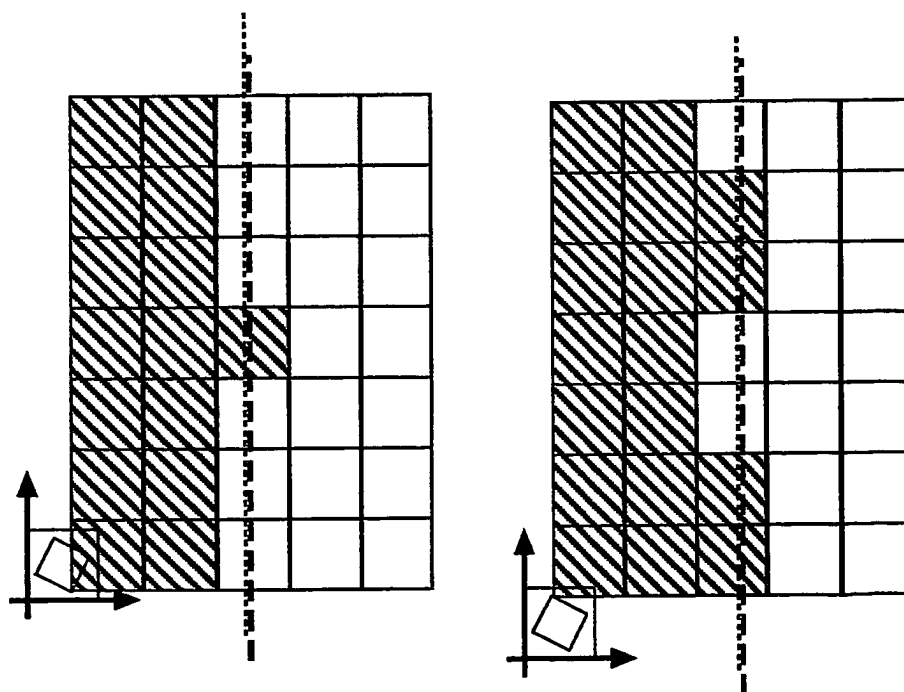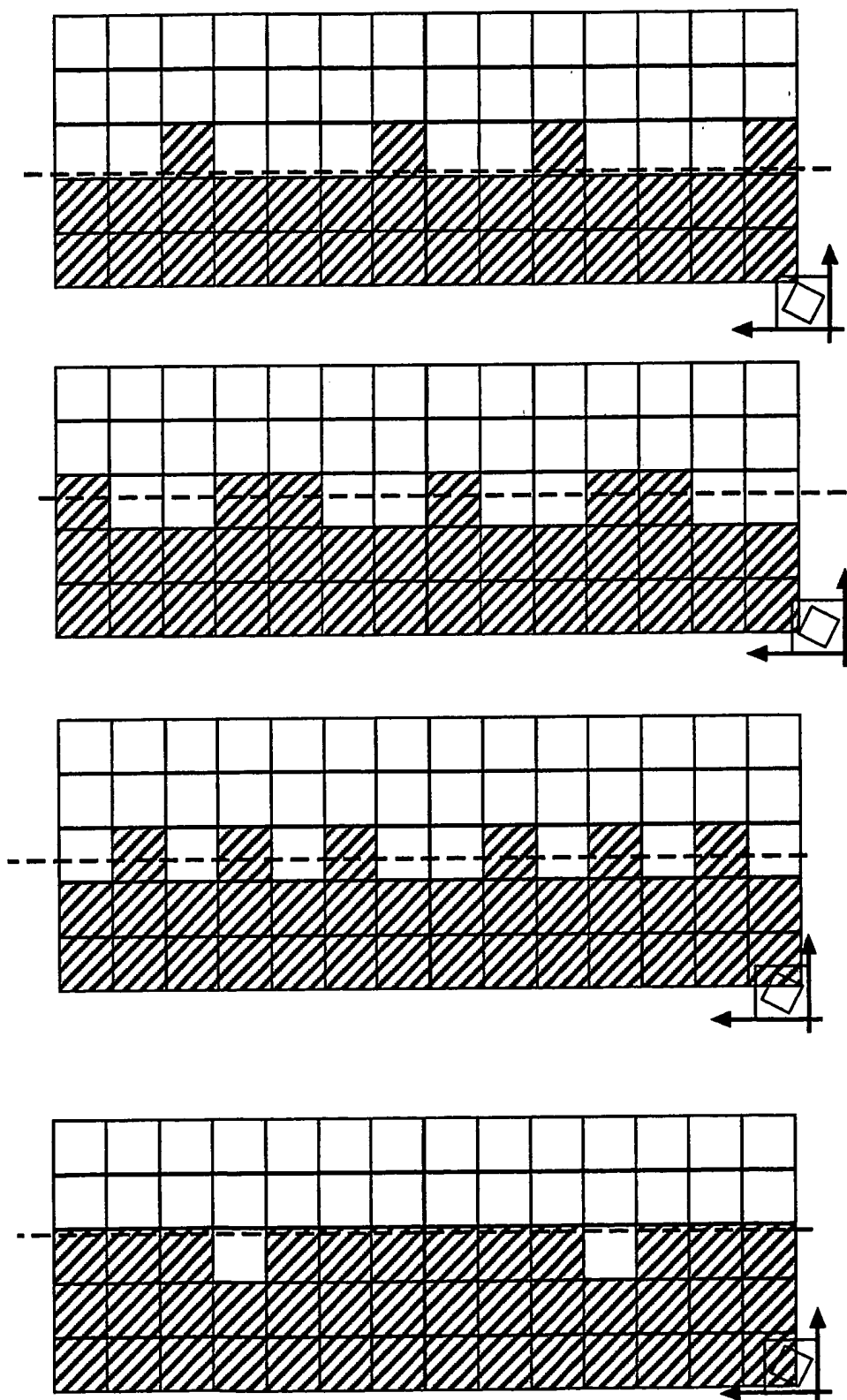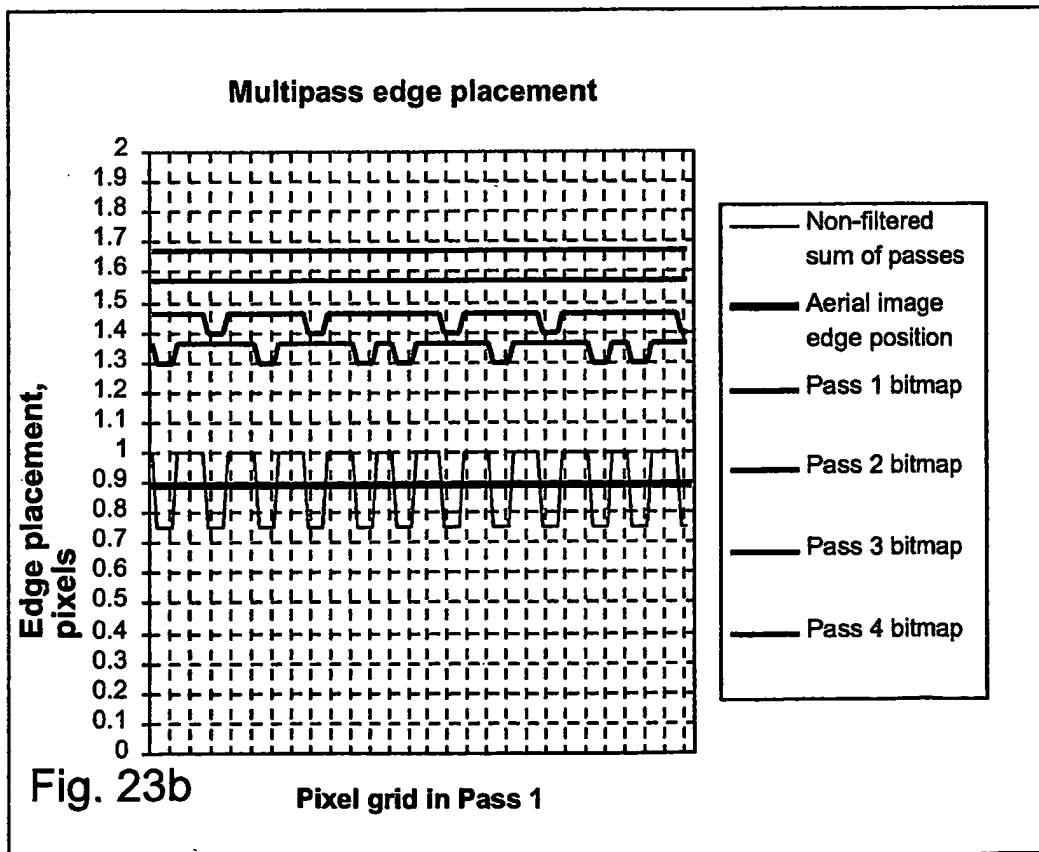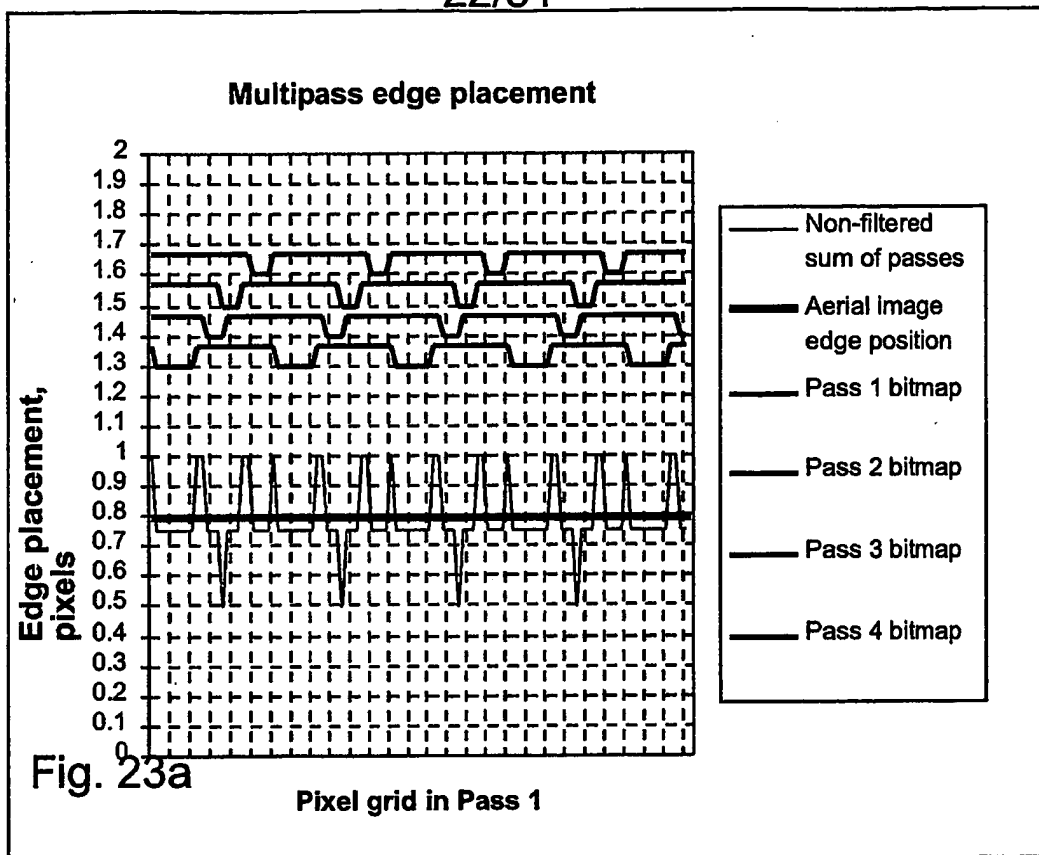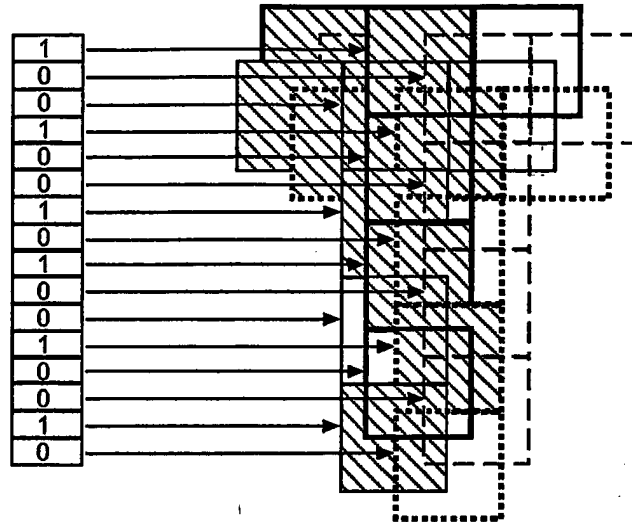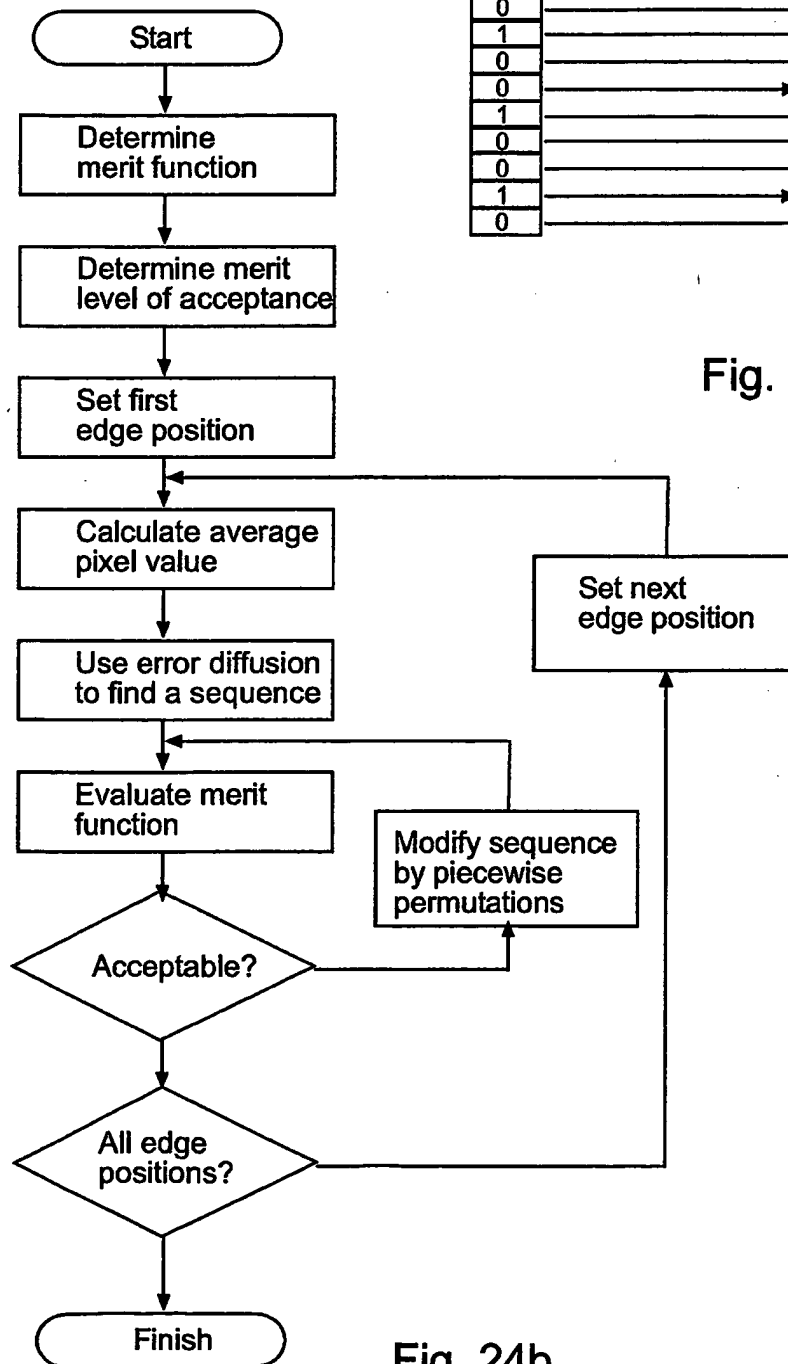
Fig. 24b
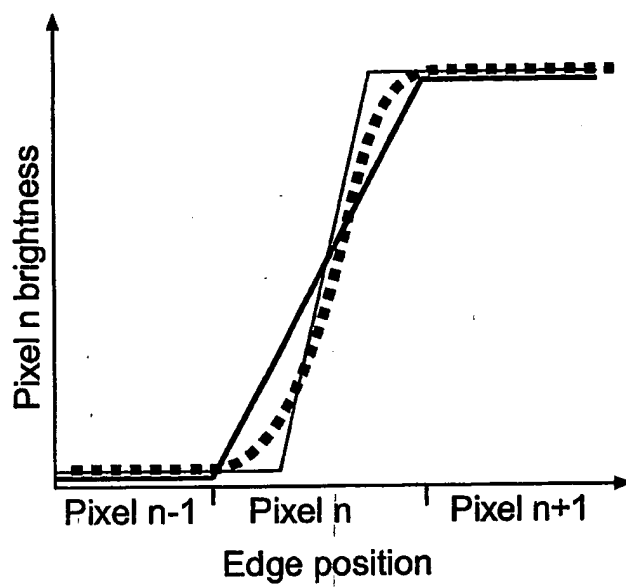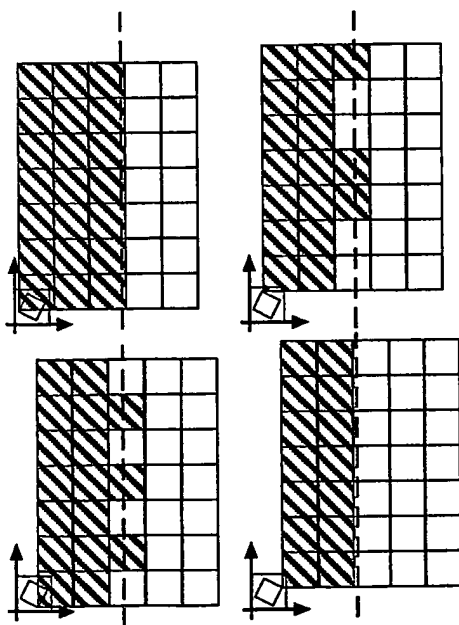
Fig. 25a



Fig. 25b
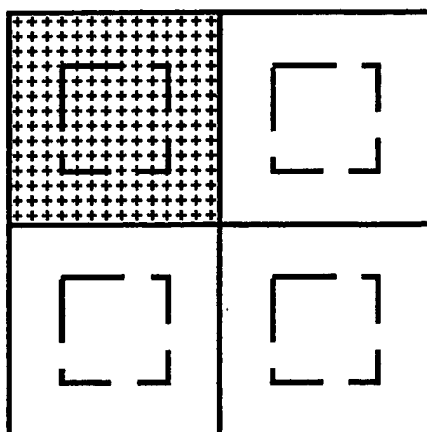
Fig. 26a



Fig. 26b



Fig. 26c

Fig. 27b



Fig. 27a



Fig. 27c
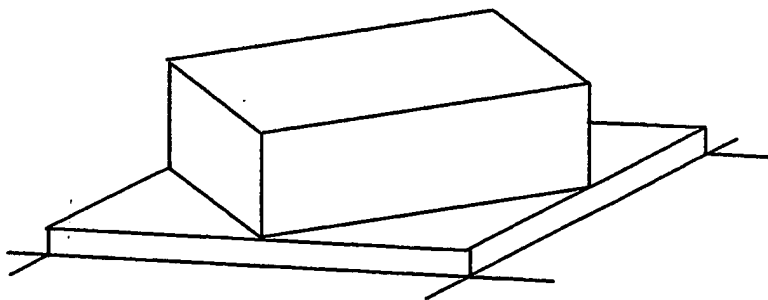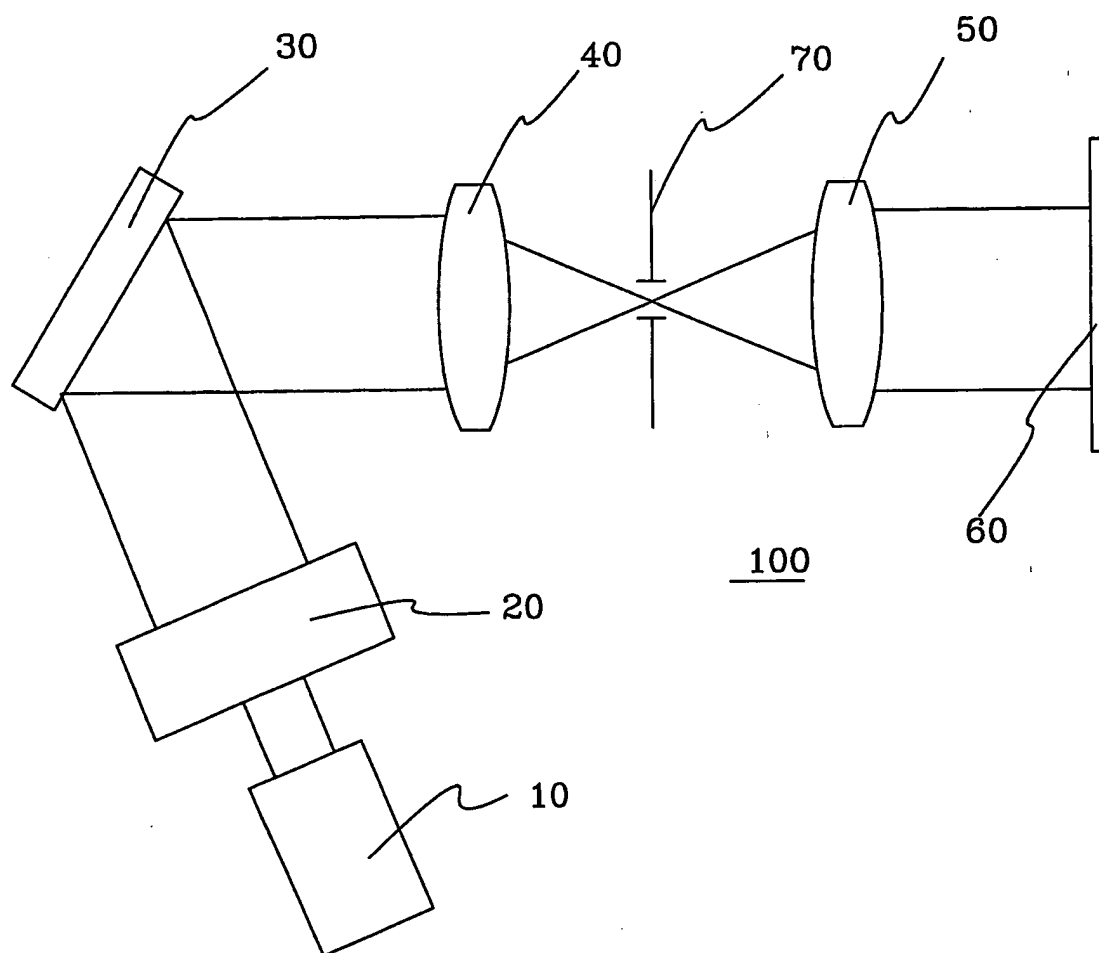
Fig. 28a



Fig. 28b

Fig. 29

|      |      | 3012 | 3013 | 3014 | 3015 | 3016 | 3017 |
| ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 3010 | 3011 |      |      |      |      |      |      |
| 0    | 0    | 75   | 100  | 100  | 74   | 0    | 0    |
| 0    | 0    | 74   | 100  | 100  | 75   | 0    | 0    |
| 0    | 0    | 75   | 100  | 100  | 74   | 0    | 0    |
| 0    | 0    | 74   | 100  | 100  | 75   | 0    | 0    |
| 0    | 0    | 75   | 100  | 100  | 74   | 0    | 0    |
| 0    | 0    | 74   | 100  | 100  | 75   | 0    | 0    |
| 0    | 0    | 75   | 100  | 100  | 74   | 0    | 0    |
| 0    | 0    | 74   | 100  | 100  | 75   | 0    | 0    |

Fig. 30

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| 0 | 1 | 74 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|----|---|
| 0 | 0 | 75 | 100 | 100 | 74 | 1 | 0 |
| 0 | 1 | 74 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 74 | 1 | 0 |
| 0 | 1 | 74 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 74 | 1 | 0 |
| 0 | 1 | 74 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 74 | 1 | 0 |

Fig. 31

| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|----|---|
| 0 | 0 | 74 | 99 | 99 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 99 | 99 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 99 | 99 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 99 | 99 | 74 | 0 | 0 |

Fig. 32

3314  3315  3316  3317

| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|---|---|
| 0 | 1 | 74 | 99 | 99 | 74 | 1 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 1 | 74 | 99 | 99 | 74 | 1 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 1 | 74 | 99 | 99 | 74 | 1 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 1 | 74 | 99 | 99 | 74 | 1 | 0 |

3310  3311  3312  3313

Fig. 33

3414  3415  3416  3417

| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|---|---|
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 100 | 100 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |

3410  3411  3412  3413

Fig. 34a

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| 0 | 0 | 74 | 100 | 100 | 74 | 0 | 0 |
|---|---|----|-----|-----|----|---|---|
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |

3414  3415  3416  3417

3410  3411  3412  3413

Fig. 34b

| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|---|---|
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 100 | 100 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |

3414  3415  3416  3417

3410  3411  3412  3413

Fig. 34c

| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
|---|---|----|-----|-----|----|---|---|
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |
| 0 | 0 | 74 | 100 | 100 | 74 | 0 | 0 |
| 0 | 0 | 75 | 100 | 100 | 75 | 0 | 0 |

Fig. 34d

| 1:st | 2:nd | 3:rd | 4:th |
|------|------|------|------|
| 1 | 3 | 8 | 5 |
| 2 | 7 | 6 | 8 |
| 3 | 1 | 5 | 7 |
| 4 | 5 | 7 | 6 |
| 5 | 4 | 3 | 1 |
| 6 | 8 | 2 | 4 |
| 7 | 2 | 4 | 3 |
| 8 | 6 | 1 | 2 |

Fig. 34e

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/SE 02/02310

### A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G03F 7/20

According to International Patent Classification (IPC) or to both national classification and IPC

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ, INSPEC, COMPENDEX, TDB

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 9945441 A1 (MICRONIC LASER SYSTEMS AB), 10 Sept 1999 (10.09.99), page 2, line 1 - line 4; page 8, line 24 - line 27, page 12, line 29; page 24, line 29 - line 32; claims 1 | 1,3,4,13-15, 17,18,28-31 |
| A | WO 9945435 A1 (MICRONIC LASER SYSTEMS AB), 10 Sept 1999 (10.09.99), claim 1 | 1-52 |
| A | WO 9945440 A1 (MICRONIC LASER SYSTEMS AB), 10 Sept 1999 (10.09.99), claim 1 | 1-52 |

☐ Further documents are listed in the continuation of Box C.      ☒ See patent family annex.

| | |
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| * Special categories of cited documents: | "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention |
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| "E" earlier application or patent but published on or after the international filing date | "X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone |
| "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) | "Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art |
| "O" document referring to an oral disclosure, use, exhibition or other means | |
| "P" document published prior to the international filing date but later than the priority date claimed | "&" document member of the same patent family |

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 17 March 2003 | 1 8 -03- 2003 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86 | Bengt Christensson/MP Telephone No. +46 8 782 25 00 |

Form PCT/ISA/210 (second sheet) (July 1998)

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| | | AU 2755699 A | 20/09/99 |
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| | | AU 2756899 A | 20/09/99 |
| | | AU 2756999 A | 20/09/99 |
| | | AU 2757099 A | 20/09/99 |
| | | AU 3284299 A | 20/09/99 |
| | | BR 9808505 A | 23/05/00 |
| | | CN 1292102 T | 18/04/01 |
| | | CN 1292103 T | 18/04/01 |
| | | EP 0973668 A | 26/01/00 |
| | | EP 1060439 A | 20/12/00 |
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